DESIGNING A FLEXIBLE AND RECONFIGURABLE MANUFACTURING SYSTEM CONSIDERING A CIRCULAR SHAPED LAYOUT

by

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Approval Signatures

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Dedication

To my parents…

Abstract

Production demands are constantly changing at a fast pace. The demand for a shorter life cycle and customized products makes it more difficult for factories to adapt. To stay competitive, factories need to be flexible in embracing those continuous changes. Since the second half of the last century, several advanced manufacturing systems have been developed to efficiently produce a variety of products. One of them is the Flexible Manufacturing System (FMS) that has the ability to produce different quantities of different varieties without the need to pause the production line, thus improving process efficiency and lowering production cost. FMS layout includes several arrangements of machines and material handling system and has a significant influence on routing flexibility, machine utilization, factory floor space area, responsiveness to change and productivity. In this research, a new FMS layout, composed of multiple circular loops, is proposed and compared to the traditional open field layout with rectangular loops and ladders. Face Centered Composite Design (FCCD) is applied to investigate the main and interaction effect of product quantity, variety and complexity, and layout design on system performance. The fourth categorical factor considered is the layout shape. Total production cost is used as a system performance metric. To determine this cost, a linear programming (LP) mathematical model is formulated. The model design attributes include cell layout, cell formation, machine capacities, constant and variable machine cost, lot splitting, and alternative process routings. Lingo software is used to solve the formulated optimization model which was validated by comparing it to test cases available in the literature. Response Surface Methodology (RSM) was used for modeling the responses. The main effect plots indicate that increasing the number of locations had the most significant influence on cost, followed successively by product and routing. Results reveal that proposed circular layout is more cost effective than the traditional rectangular open field layout with cost savings reaching 14 % and more when product variety and complexity is increased.

Keywords: ***Flexible manufacturing system; machine grouping; cell layout; circular layout; loops layout; open field layout; Design of Experiments.***

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List of Abbreviations

AGV	Automated Guided vehicle.
C	Circular layout.
CMS	Cellular Manufacturing System
DOE	Design of Experiment.
FCCD	Face Centred Composite Design.
FMS	Flexible Manufacturing System.
GA	Genetic Algorithm.
GT	Group Technology.
ICMD	Inter-cellular movement distance.
L	Location.
LCS	Longest Common Subsequence.
LP	Linear Programming.
M	Machine.
MBO	Migration Birds Optimization.
MMBO	Modified Migration Birds Optimization.
NILP	Nonlinear Integer Programming.
P	Product.
R	Rectangular shape/ Open-field layout.
RMS	Reconfigurable Manufacturing System.
RSM	Response Surface Methodology.
SA	Simulated Annealing.
SCS	Shortest Common Subsequence.
WIP	Work In Process.

Chapter 1. Introduction

A manufacturing plant consists of processes, systems and people that are necessary to convert raw materials into finished products of higher economic value. This is achieved by the application of physical and chemical processes to alter raw materials' geometry, properties and appearance. The potential of the manufacturing process depends on the technological capability, production capacity and physical product limitation [1]. A company designs its manufacturing systems and organizes its factories in such a way that maximizes the efficiency of its production plants [2]. The quantity and variety of products produced influences the way the facility is organized.

1.1. Types of Manufacturing Layout

The type of layout depends on the factory's supply of products, in terms of the annual production quantity and variation of items. Figure 1.1 illustrates the different types of layouts and how they are influenced by the quantity and variety of products. The most common layouts include product, process, mixed, fixed and cellular layouts.

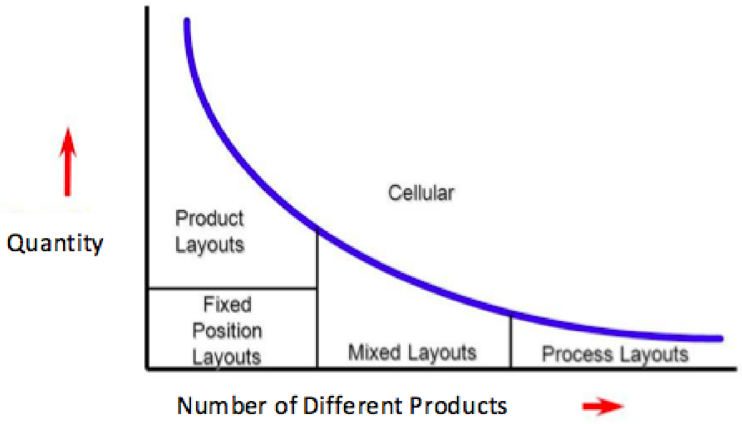

Figure 1.1: Relationship between product volume and variety [3]

A product layout is utilized when the quantity of a single item is high enough to be produced in an individual production line. The arrangement of all machines that are required for the production line is being done according to the processing sequence of the item. This arrangement increases the flow efficiency of materials and reduces the cost per unit [4][5]. Product layout is ideal for high-quantity production and can reduce material handling, hence costs. It also eliminates work in process (WIP). Another benefit of product layout is the high utilization of labor and machines and minimization of manufacturing time. It facilitates production planning and control, which smoothens the sequence of production tasks[6]. On the other hand, there are some limitations associated with product layout, such as high investment, inflexibility and high sensitivity. There is no flexibility regarding changes in the process or time management, and the layout is sensitive when a machine breakdown or maintenance leads to the shutdown of the whole line.

The process layout, or functional layout, is the design where machines that perform similar functions are grouped together at one location. This layout produces high variety of products or customized products with limited quantities. Production is being represented in batches or lots [6] [7]. Other benefits of this layout are associated with lower initial investments, fewer machines as well as equipment flexibility. The machine utilization rate is significantly low since production is customized, depending on how the products are processed. There are some drawbacks of the process layout. One of them is that material-handling systems cannot be automated, which extends the duration of the process. It is also assigned with a high number of setup times since the production type changes according to demand, which results in lower productivity [8].

A mixed layout is a combination of product and process layout, deriving the benefits of both. It is useful when producing the same product in different sizes or shapes. This type of layout is similar to the process layout in terms of the way the machines are arranged; however, the production process is designed as in the product layout in terms of the arrangement of the sequence of operations [6] [7]. In the fixed position layout, the location of the product is fixed because the transportation cost is significantly high due to the high weight of the product. The material remains fixed, while all machines and tools are moved around it [6] [7].

Cellular layout is also a combination of the process and product layouts. It refers to a function of group technology (GT) in which dissimilar machines or procedures are being grouped as cells. GT takes advantage of soft product variety between products by utilizing similar processes and tools to produce them. Machines are grouped into work cells; each cell specifically produces a family of parts [6] [7].

Cellular manufacturing can be implemented by manual or automated methods. When automated, it is often referred to as flexible manufacturing system, which is one of the most common types of advanced manufacturing systems [4].

1.2. Advanced Manufacturing Systems

In traditional manufacturing systems, production requires long set-up durations, with labor activities put on hold until the set-up is complete. As a result, there was need for industries to develop systems that are more efficient, flexible, and productive. These are referred to as *Advanced Manufacturing Systems*. The first and simplest type is the *Flexible Manufacturing System* (FMS), which has the ability to produce a variety of products without any time lost while reprogramming the system. This system can produce several products, within limited number of families of parts, without the need to produce in batches [4]. It produces a minimal number of families of parts. The second type is the *Reconfigurable Manufacturing System* (RMS), which is designed so that its production capacity can be increased or reduced, and its physical structure can be quickly reformed, so that it can produce a variety of styles without any major reformations to the layout.

Any manufacturing system is referred to as “Flexible” if it has the ability to identify the different input parts, which allows for fast transition of process instructions, and the objective setup. FMS system may include as many as 20 machines; small systems of one or two machines are usually referred to as "flexible cell’ Spena *et al*. (2016) [2] distinguish seven types of flexible manufacturing and assembly systems: variant, quantity, technology, successor, external, internal and personnel flexibilities. Variant flexibility is the ability to manufacture a variety of products; quantity flexibility is the ability to produce different products in different quantities; technology flexibility is the ability of the manufacturing system to handle multiple amounts of technologies; successor flexibility is the ability to use equipment or parts for future products; external flexibility is the ability to change the system by exchanging elements; internal flexibility is the ability to change the system without modifications (example automatic tool change), and personnel deployment flexibility is the ability to operate with more or fewer employees with different qualifications.

FMS layout can vary, depending on the arrangement of machines and the material handling system [9] [10]. The simplest form is the in-line layout, which represents an arrangement of a straight-line flow in one direction. This layout does not have a secondary handling system; hence, all units must pass only once through all machine units. Figure 1.2 represents an in-line layout with a secondary material handling system. Adding a secondary handling system could facilitate flow so that it can move in both directions, in addition to providing a temporary storage of parts at each station. An in-line FMS layout can also be integrated with a part storage system.

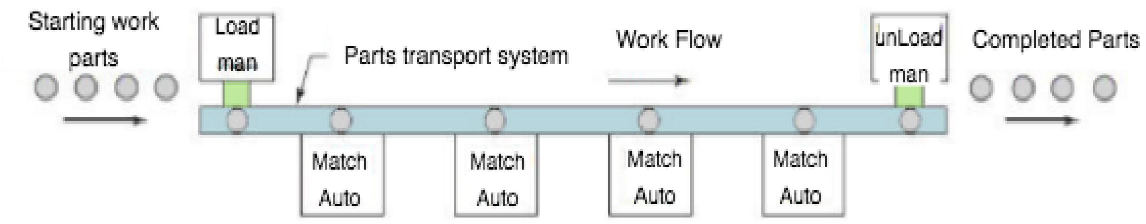

Figure 1.2: In-line FMS layout [2]

Another common layout is the FMS loop (circular shape) layout. This type basically consists of a circular loop material handling system attached to machine cells through a secondary system. The material handling here travels in one direction. However, a variation in processing sequence is possible for different part types since it moves. This layout allows parts to be stopped and transferred to any station as illustrated in Figure 1.3. Alternatively, the loop layout could be rectangular as seen in Figure 1.4. The rectangular form of the layout allows for recirculation of pallets back to the first station of the sequence after unloading at the final station.

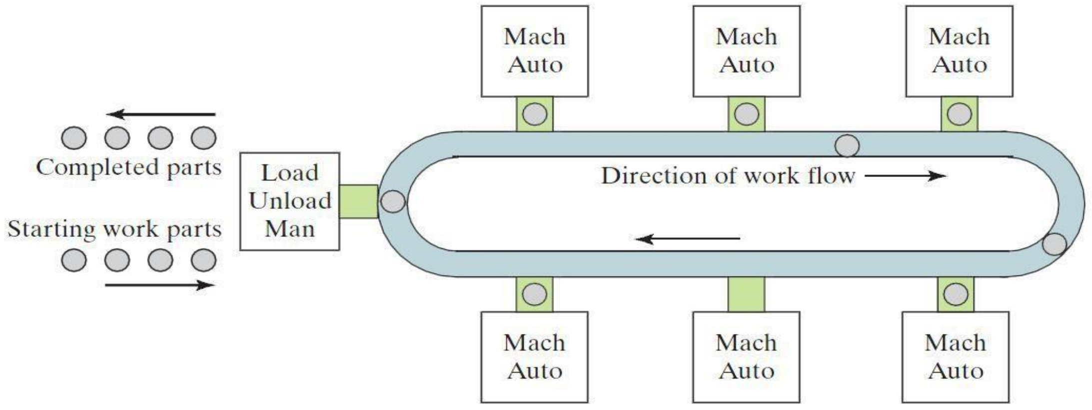

Figure 1.3: FMS Loop layout [2]

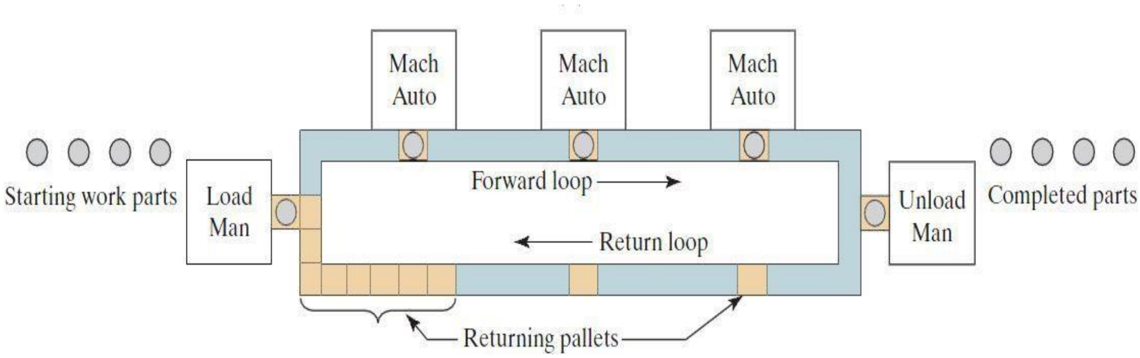

Figure 1.4 FMS Rectangular Layout [2]

The above-mentioned layouts are designed to produce a limited variety of part styles. In many cases, the parts to be made on the system should be known ahead of time. Figure 1.5 illustrates an open field layout, which contains multiple loops and ladders, hence, making it suitable to process large families of parts. The parts are routed to the different workstations depending on the ones made available first.

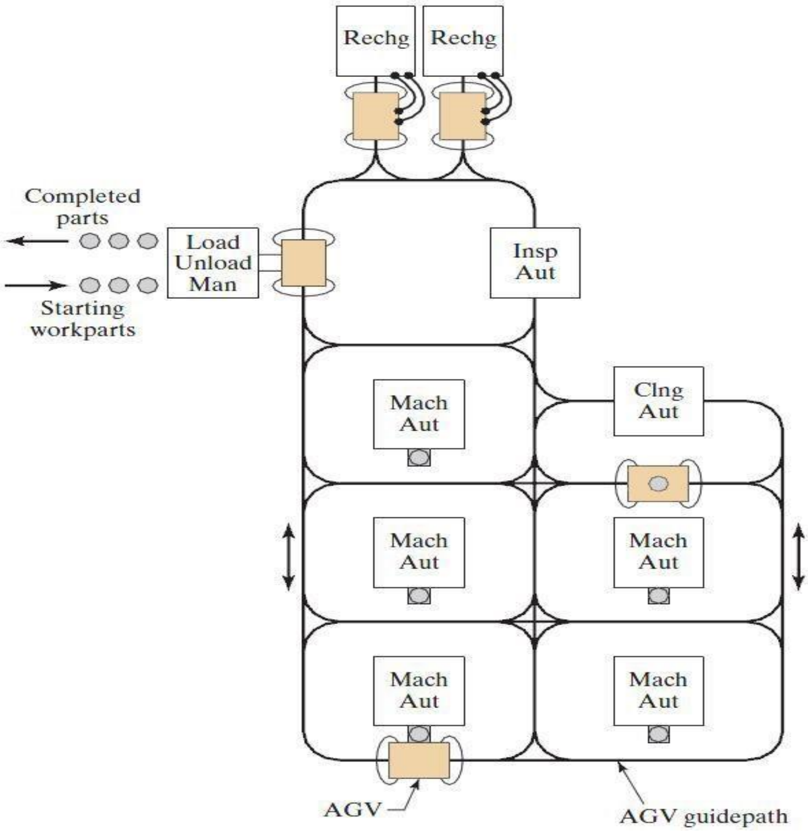

Figure 1.5: FMS open-field layout [2]

Although FMS system is expensive to implement, it provides significant savings. It can address growing customer demands for quick delivery of customized products with the benefit of reductions in variable cost and throughput time, which leads to the capacity for making customized high-quality products with small lot sizes and short lead times. FMSs can produce a wide variety of products with much higher productivity when compared to traditional manufacturing systems. In addition, machines can be kept running for up to three shifts with a lower crew level since everything is programmed and automated. In spite of those advantages, it is limited to a small number of families of parts. The most critical issue is determining the optimal design of FMS, which is a very complex problem [8]. The demand for customized products is increasing and the cost of coping with this is high when applying FMS for the production of low quantities of items. With FMS, factories will have to raise their expenditure, mainly because this system produces a limited number of parts. In order to follow the continuous change in market demand, manufacturers have to reconfigure their cells, which can contribute to a significant high cost if the process is repeated.

The main difference between FMS and RMS is that FMS seeks to increase the variety of part products, compared to RMS which aims at increasing the speed of production in response to the customers' demand. RMS, also known as *Changeable Manufacturing System* [11], is designed so that its production capacity can be increased or reduced, and so that its physical structure can be quickly reformed, in order to produce a different variety of parts without any major reformations to the layout. It was introduced when companies required a system that is capable of being changed in a rapid cost effective manner, which will enable it survive in the industry [12]. This system was developed in 1999 in order to reduce the cost of moving product parts, the cost of moving machine cells, as well as the cost of material handling. Its layout is somehow similar to the FMS open-field layout. However, the main focus of RMS is to produce part families, allowing machine cells to be adjustable and system flexibility to be customized. RMS deals with challenges associated with the setup time, the time to design, and the reconfiguration of machine cells; its objective is to reduce these times. The features that characterize RMS are customized flexibility, convertibility, scalability, modularity, integrate-ability, and diagnostics-ability. Any system that consists of some or all of these characteristics can be referred to as RMS. Hence, FMS can be considered as a type of Reconfigurable Manufacturing System (RMS). The more changeable a system is, the better it adapts to the principles of recycling, reusing, reducing [13]. Table 1.1 illustrates distinctive features in each of the three systems [14].

Table 1.1: Comparison between traditional, FMS, and RMS [17]

	Traditional	**RMS**	**FMS**
System Structure	Fixed	Adjustable	Adjustable
Machine Structure	Fixed	Adjustable	Fixed
System Focus	Part	Part Family	Machine
Scalability	Non	Yes	Yes
Flexibility	Non	Customized	General
Simultaneously Operating Tool	Yes	Yes	No
Productivity	High	High	Low

1.3. Research Objectives

Industries are facing challenging times, something that requires them to continuously produce customized products with shorter life cycle. To achieve this, they need to maintain a flexible and reconfigurable layout to meet demands. To stay competitive, they also need to ensure the costs of such systems are minimized. This conflicting interest of minimizing cost while satisfying customer needs has to be addressed. A modified layout design could be the key to delivering a system that has the advantages of both reconfigurable and flexible features. An appropriate layout design could reduce the cost of transporting product parts and moving machine cells, while enhancing production performance with respect to of product varieties and quantities. The objective of this work is to propose a modified layout that combines both features of FMS and RMS to achieve this goal. The purpose of this layout is to increase the variety of products, while producing the maximum number at minimum costs. The main challenge is being able to optimize the system while faced with limitations with respect to aspects such as facility space, machine units, product routing and the areas, attaining maximized utilization of machines and minimum WIP. Consideration is given to the grouping of machines into work cells and the location of the machines within each work cell. The proposed layout will be compared to the traditional open field layout with rectangular loops and ladders (Figure 1.5) to determine its effectiveness.

The objectives of this research work is to:

- design a modified layout that provides a material handling solution that is more flexible and configurable in comparison to the traditional FMS open field layout.
- formulate a LP mathematical model that minimizes production cost by integrating both cell layout and cell formation decisions.
- Use lingo to solve formulated LP model to determine optimum total production cost under different scenarios
- use DOE, regression analysis and statistical tools to investigate the main and interaction effect of product quantity, variety and complexity on system performance (optimum production cost) for traditional and proposed layout.

1.4 Thesis Structure

The remainder of this thesis is organized as follows: Chapter 2 provides the background of FMS layouts, problems encountered and the approaches used to tackle them. The proposed layout is discussed in Chapter 3 along with the mathematical formulation and algorithms used to optimize the layout. Chapter 4 presents results and analysis section. It includes mathematical model validation by comparing model results with a case study from literature, illustrative examples to demonstrate clustering behaviour for various layouts, DOE and performance evaluation comparing the proposed layout with the current traditional one. The final section, Chapter 5, concludes the thesis.

Chapter 2. Background and Literature Review

This chapter discusses analysis techniques used by researchers to plan and design, and the operational issues related to FMS and RMS. Understanding progress in this area would provide an insight that will help to develop the proposed layout, to determine the best formulation for the problem and the best solution methods. Several approaches are used to analyze systems, ranging from deterministic models to discrete event simulation models. Deterministic models such as the bottleneck/extended bottleneck can be used to estimate production rate and utilization. In spite of their simplicity and ease of use, they do not permit the evaluation of operating characteristics and system dynamics. Other methods like queuing models could be used to account for some of those dynamics. Discrete event simulation could also be utilized in modeling specific aspects of the system. Mathematical programming is one of the most widely used tools to tackle this problem in order to achieve different system performance objectives.

Erdin and Atmaca [15] used the bottleneck model and clustering techniques to design an FMS. The bottleneck problem was solved by calculating utilization. The sequence of workstations and plant layout was determined for a given production of different parts, processing sequence and time. Results were compared with the traditional manufacturing system to determine the effectiveness of the implementation. It showed that the total travel distance and time for the parts in the system were lower in the FMS. Furthermore, the efficiency of the system has increased through the reduction of idle times of workstations. The overall utilization of the system was calculated to be 95.3%, which is significantly higher than the existing traditional manufacturing system.

Niroomand *et al.* [16] stated that 20-50% of the total cost in flexible manufacturing system comes from material handling. They claimed that material handling cost depends on the layout type and the way the material handling paths are placed. They also assumed that material handling cost could be reduced by applying an efficient layout. The Modified Migration Birds Optimization (MMBO) was proposed to improve the facility layout through the use of an arbitrary solution, and by randomly generating a sequence of cells placed around a closed loop with a given size, and by computing the cost of the layout. This is labeled as the main solution. A swapping procedure is then used to generate the neighbors of the main solution, and a better cost is being chosen as the optimal cost. Following this, the size of the closed loop is decreased by a unit and the procedures above are repeated with the new size each time the loop is decreased until the minimum feasible size of the closed loop that is enough for locating the cells is reached.

The MMBO method tries to replace each main solution by a new neighbor, if it exists, to achieve better cost. Some assumptions are taken into consideration such as the limitation of the floor and material handling path, and the lack of space for straight-line layouts. The algorithm uses natural and logical rules to solve the model problem by combining the logics of geometry and human intelligence through the use of logical functions in computer programming to arrange the cells around a rectangular closed loop without overlapping. The limitation of this approach is the non-deterministic polynomial-time hardness of the model that makes it difficult to reach a good and feasible solution, especially for large size problems. Niroomand *et al.* [16] suggest the combination of the standard Migration Birds Optimization (MBO) method with other meta-heuristics as a possible way of hybridizing the MBO algorithm.

Tolio and Urgo [17] observed a significant influence on the cost of configuration and reconfiguration when using Linear Programming (LP) models to investigate the configuration of a mixed-model transfer line in which the objective function is to minimize the equipment costs. It was assumed that the setups definition, optimal sequencing, and batches dimension were given. The concept of the experiment is that the part to be manufactured is fixed on a rotating table and is surrounded by machines.

Guo-xin, *et al*. [18] used experiments to relate the formation of families of parts, which consider bypassing moves, with idle machines. Their method was to identify the longest common subsequence (LCS) among different part processes, then, combine the (LCS) with the rest of the operation, and at the same time consider bypassing move and idle machines, in order to create the shortest composite subsequence (SCS) based on the (LCS). Based on the linear relationship of the similarity of parts between (LCS) and (SCS), a coefficient algorithm was computed as a basis for part clustering and family formation. The coefficient algorithm was compared with existing systems to verify its efficiency and accuracy. The algorithm provides a higher computational efficiency, and as a result, the accuracy of the part family division was relatively satisfactory. Future research can comprehensively consider various internal and external influencing factors that improve the accuracy and practicality of the part family construction.

Neufeld, *et al.* [19] reviewed problems that may occur in flowshop group scheduling. Several issues were identified such as flowshop group scheduling with single machine, cellular manufacturing scheduling, minimization of inter-cellular movements, and lot streaming. These problems depended on the nature of the shop environment, the number of parallel machines at each stage, the number of independent manufacturing cells and machines, and the kind of setup times. However, the researchers did not offer any solution to the problems identified.

Yu and Sarker [20], and Filho and Tiberti [21] applied machine grouping solutions to solve product parts routing as well as minimize inter-cellular movement costs. Yu and Sarker used an LP model to create an optimal solution regarding the second stated problem. The bottleneck problem was neglected in the paper in favor of machine-cell location. Filho and Tiberti [21] used a special class of algorithm called Genetic Algorithm (GA), which is based on the principles of genetics and natural evolution theory.

Mahdavi, *et al.* [22] applied a machine location approach, while minimizing inter-cellular movement cost and cell decomposition, in order to solve cell formation and cell layout problems with a single formula. The aim was to group similar parts (clustering) and corresponding different machines in the same cells, and use forward and backtracking movements by employing nonlinear integer programming (NLIP). The objective function was to minimize three cost components: the cost of intra-cell forward and backward movements, the cost associated with machines' position inside their assigned cells, and the cost of inter-cell traveling distance. This experiment resulted in the minimization of intra and inter-cell movements along with exceptional elements. Further research is suggested by Mahdavi, *et al.* [22] to develop meta-heuristic methods for real- size problems and apply fuzzy stochastic considerations into the proposed model.

Chang *et al.* [23] examined the problems of cell formation, cell layout, and intracellular machine layout. They formulated a two-stage mathematical programming model in order to solve the three critical problems, while considering operation sequences, alternative routing, production volume, and different cellular layout types. The first stage of the process indicated that cell formation and cell layout must be solved in order to proceed to the next stage, which implies that the objective function is required to minimize the inter-cellular movement distance (ICMD). The second stage was to determine the machine layout in each cell on the basis of the cell formation computed in stage 1. Chang *et al.* [23] indicated that this model increased both efficiency and effectiveness in Cellular Manufacturing System (CMS). They also specified that in the future a solution scheme could be developed that concurrently considers the three critical problems and provide optimal decisions. Other problems that may be included in the current model are related to items such as part scheduling, production resources allocation, machine reliability, and the inclusion of several cell layout types.

RMS has been considered as a means of controlling material transfer and minimizing its cost. Both Kia *et al*. [24] and Kioon *et al*. [25] used this approach along with Cell Formation in order to solve several problems associated with, e.g., inter-cellular layout, intra-cellular layout, cell formation, alternative process routing, lot splitting, duplicated machines, operation sequence, processing time and machine capacity. The method was used to apply non-linear programming mainly to improve the design of a cellular manufacturing system (CMS) by integrating cell formation and group layout under a dynamic environment. Kioon *et al.* [25] also solved some random small- scale problems. The main assumption was that production mix or volume changes in demands can be forecasted, making it possible to conduct multi-period plans. Koon’s model can still be modified to include additional features, such as the ability to hold inventory between periods, partial or total subcontracting, workload balancing among the cells, optimization of number of formed cells, machine utilization, batch material handling, management of part demand uncertainty, information on machine availability and cost coefficients, multi-objective optimization and management of unequal area facilities.

The criterion for solving the previous approach was also used by Baryam and Sahin [3]; however, they applied linear programming in which the problem was divided into two heuristic solution methods: one that combines Simulated Annealing (SA) with Linear Programming and the other that combines Genetic Algorithm (GA) with Linear Programming. The objective function was used to minimize inter- and intra-cellular material handling cost, installation cost, and uninstallation cost. Future work is recommended by Baryam and Sahin [3] to incorporate other design features of CMS into the model as well as to other important features that can be incorporated, such as the time value of the money, inventory holding and outsourcing. In addition, integration of other meta-heuristics with LP can also be taken into account.

Delgoshaei and Gomes [26] applied outsourcing solutions by finding the best production strategies of in-house manufacturing and outsourcing in small and medium scale cellular manufacturing companies. Aspects investigated were minimization of material transfer cost, machine underutilization, cell reconfiguring and dynamic part demands. A flowchart was used to facilitate the process and to consider preventive activities that could be added to the mathematical model. The objective function is formulated so as to minimize the setup cost for each machine along with the operation cost, purchasing and removing costs of machines, and preventive maintenance and emergency activity services costs. Future work is yet needed to consider multifunctional machines and operators for operating re-entrant parts.

Turgay [27] proposed various decision-making rules for the Agent- Based Flexible Manufacturing System control. Applying these rules, it would be possible to develop and improve decision-making and self-learning systems through the integration of agent systems. The scheduling activities obtained according to the sequencing of parts were evaluated in terms of time durations. However, emphasis was only on operational constraints which were listed as follows: input sequence and number of parts into the system, scheduling parts to machines based upon alternative routings, sequencing parts on machine, and scheduling material-handling devices such as AGV. In the future, other capacity constraints could be added to the problem such as number of part and types, tool magazine capacity, capacity of the material handling system, type and size of buffers, number of pallets, number and design of fixtures, and allocation of pallets and fixtures to part types.

Defersha and Hodiya [28] stated that facility layout problem is a major purview to optimize the location of machines and departments by minimizing the material handling while improving its efficiency. They came up with some configurations in their article showing cases of cellular layout as a result of relatively stable mix of products and demands. These cells can be also identified as families/ machine cells. Meanwhile, they recommended a distributed layout when the product demand and mix are rapidly changing. They were concerned about linking the gap between a couple of layouts by integrating a mathematical model. This model minimizes the inter cellular cost by optimizing the distributed layout.

Feng et al. [29] inspected the relationship between cell layout problems and cell formation. They computed a model with some specific features such as different machine dimensions, similar machine types, different routing types, and lot splitting. The method used is linear programming (LP) through which the length of cells is calculated according to machines' dimensions that are placed inside it.

Several approaches have been adopted to enhance the flexibility and configuration of the manufacturing system. Some researchers considered several consecutive or simultaneous decisions to reach a better layout; others focused on developing methods to to reach a better solution to such a complex problem. Most of the surveyed literature reveals that researchers are on the hunt for new methods and techniques to develop a better system efficiently. Research in the field shows that the benefits that could be realized by combining FMS and RMS is yet to be investigated.

Chapter 3. Methodology

In this chapter, modifications to the traditional FMS open field layout is proposed and discussed. The proposed layout consists of potential locations where machines can be allocated in the facility. An LP model is then formulated to optimize the design of the proposed layout. The objective of the model is to allocate machines to available locations in the layout and group machines into work cells. The idea is to integrate both cell layout and cell formation decisions so that total production cost is minimized. Lingo software is used to code and solve the formulated model which is then validated by comparing it to an existing case study from the literature and other simple cases to demonstrate its advantages. To evaluate the effectiveness of the proposed model, DOE is utilized. Face Centered Composite Design (FCCD) is used to study the main interaction effect of product quantity, variety and complexity as well as layout design on system performance. Four factors are examined: the total number of different parts/part styles produced, number of operations/ processing steps to make a part, number of locations available for machine placement in the facility and the layout (proposed Vs traditional). Total production cost is calculated using LP model which is used as a system performance metric. Response Surface Methodology (RSM) was used for modeling the responses (optimum total production cost) in terms of the factors studied. The above- mentioned steps will be elaborated in more details in the following sections.

3.1. Proposed layout

In designing FMS layout, the objective is to achieve random independent movement of parts between stations with greater routing flexibility and to handle a variety of part styles without excessively increasing the material handling cost. Open field layout (Figure 1.5) represents a random order FMS which is appropriate for large part families simultaneously producing different parts, allows greater variation in processing sequence and is more flexible. With this type of layout, the number of machines increases excessively.

The idea is to propose a layout with equal distance between machines. A circular layout is recommended to achieve this target since any point at its boundary is at an equal distance to any other point on boundary that can be reached by crossing through the center. This layout was used in a robot- centered cell layout where all the machines surround the robot in a circle. This layout (Figure 3.1) allows parts units to travel directly in a sequence without passing by redundant machine cells.

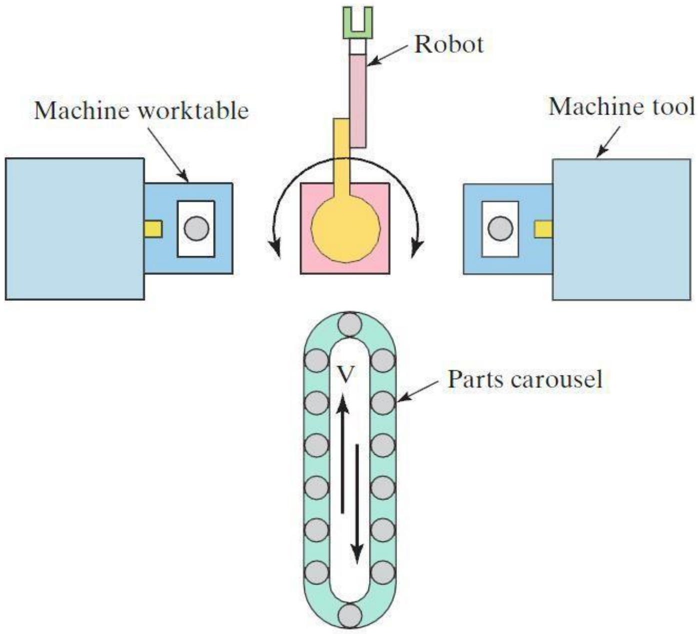

Figure 3.1: FMS Robot-Centered layout [2]

The proposed model combines the advantages of the traditional FMS open-field layout model (Figure 1.5) and FMS Robot-centered layout model (Figure 3.1). This layout will then be formulated by applying RMS design so that the change in positions will be at minimum. The resulting layout will be a circular layout that looks like a robot-centered layout; however, the material handling is automated guided vehicles (AGVs) similar to the open field, illustrated in Figure 3.2. The area, shaded green in the proposed circular layout, represents the aisle space where the material handling system will be installed. AGVs are recommended in this layout to allow movements in both directions between the machines. Each location (loc1-loc14) represents a potential area where a machine can be located if needed. Machines will not be assigned to locations based on sequential order. Section 3.2 will describe the mathematical model formulated to determine how machines are allocated. Depending on the available facility area and the size of the machines, more loops of available locations can be added. Figure 3.2 shows that the first layer has fewer possible locations, which increase with each additional loop. The main disadvantage of the proposed system is the assumption that the available facility space is square in dimension. The layout has an inner circle with radius r_0. This area should be big enough to allow the AGV to maneuver, change direction or cross over to the other side

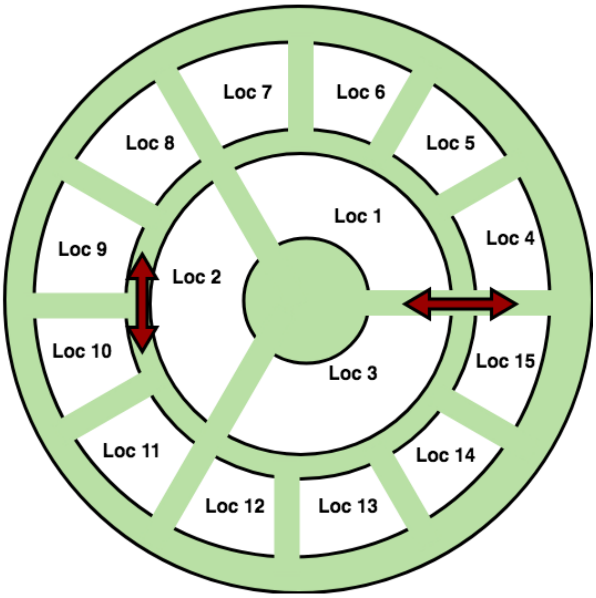

Figure 3.2: Proposed circular layout

It should also be noted that in the proposed layout, rectangular shaped machine can be oriented either horizontally or vertically as illustrated in Figure 3.3. The maximum number of locations a circular shaped layout can include depends on several parameters: inner circle radius r_0, length and width of the machine, aisle space between machines and orientation of the machines whether horizontally or vertically.

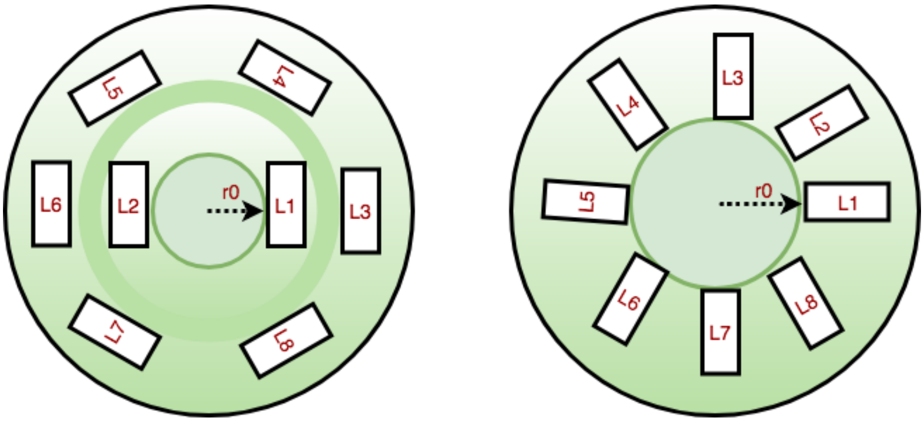

Figure 3.3: Proposed circular layout (a) horizontal, (b) vertical

To illustrate further, the facility is assumed to be square in shape with a length *By* and an area (By^2). This area will be divided into circular loops with locations that can fit machines with length L and width W. Machines can be oriented in any direction (vertical or horizontal) as long as the number of locations in this given space is maximized. Depending on the orientation of the machines, whether horizontal or vertical, the maximum number of loops will be determined. In each loop, locations will be distributed so that the machines lie along the perimeter of the inner loop. The maximum number of machines that can be accommodated in a specific area will depend on the number of loops and the number of machines each loop carries. The number of loops varies with *By*, r_0, machine orientation and dimension and aisle space. For a given area, machine size and the required aisle space, r_0 and machine orientation can be selected so that the number of locations in a given area is maximized. The following steps were coded using Matlab software to determine the maximum number of machines as r_0 changes. Code is available in the appendix E.

- Given facility area By^2, length of machine L, width of machine W, orientation of the machines wither they are horizontal or vertical, aisle space A.
- Calculate the number of loops depending on orientation of the machines.
- For each loop, determine the inner radius and number of machines in each loop.
- Determine the total number of machines for a specific r_0 and facility area By^2.
- Plot the maximum number of machine as the r_0 changes and *By* changes.

Figure 3.4 shows the maximum number of machines for horizontal and vertical orientation as r_0 increases for an area = 18 m^2, machine dimensions = 1.5x0.75 m^2, aisle space = 0.5 m. As seen from the figure 3.4 (b), the maximum number of machines is not a continuous function of the r_0. As the r_0 increases (from 0.25-1.25 for horizontal layout), the perimeter of the loops also increases which allows more machines to be laid next to each other in one loop increasing the number of machines (from 12 to 22). If r_0 is increased further, the number of loops will decrease by 1 loop at a time which will leads to a reduction in number of locations dropping suddenly (from 22 to 12 again as r_0 is increased from 1.25 to 1.5). When designing the layout, the value for inner circle r_0 should be selected so that the layout has the maximum number of loops with the largest circumference in total. This will give a layout with maximum number of locations.

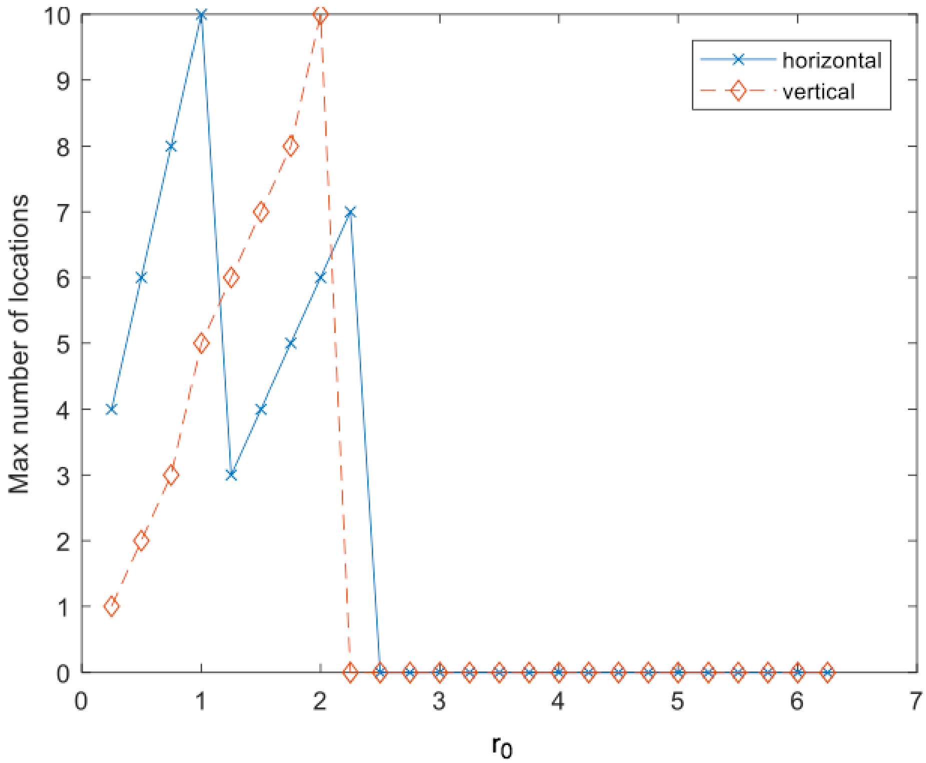

Figure 3.4(a): Maximum number of locations to fit in a circular area with By =6 and different r_0 values.

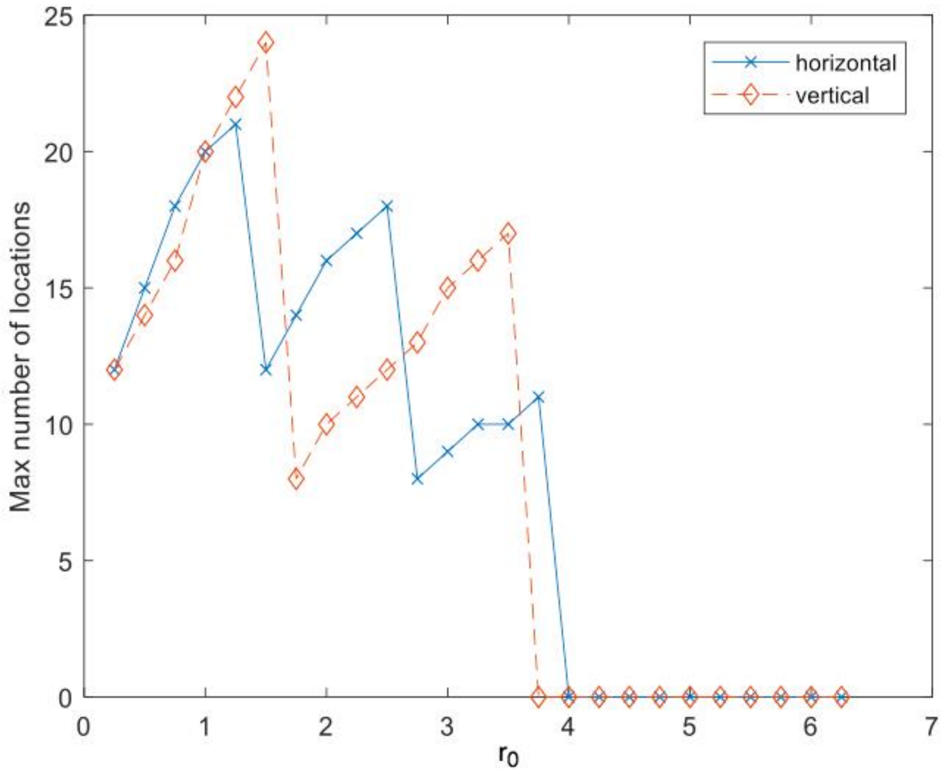

Figure 3.4(b): Maximum number of locations to fit in a circular area with By =9 and different r_0 values.

3.2. Problem Formulation

In the previous section, a layout is proposed where the factory floor area is divided into locations as shown in Figure 3.2. The objective at this point is to allocate machines to those locations so that the flexibility and responsiveness to increases in demand or need for customized products can be achieved at minimum cost. To achieve this, a LP model that considers numerous aspects of Dynamic Cellular manufacturing System (DCMS) design is devised. This model follows similar formulations and assumptions to those proposed by Kia *et al.* [24] and Baryam and Shahin [3]. The model integrates both cell layout and cell formation decisions so that total production cost is minimized. It considers inter and intra-cell layout design and material handling costs, alternative process routing, operations sequence, lot splitting, variable and fixed machine costs, machine purchasing decisions and costs, installation and uninstallation of machines.

To perform this assignment, an optimization model was developed with an objective to minimize the total cost including handling and operation subject to some constraints. It is assumed that a given factory wants to produce p types of different products, each with a certain demand D_p. Each product p needs to go through a set of operations r, and each operation can be performed on one or more machine i. α_{pri} indicates if a machine is capable of performing that operation on this product. Throughout the model, it is assumed that all products need to go through the same number of operations, but the operations and routing is different. Processing time π_{pri} for a specific product and operation is different if performed on a different machine. There is a set of m machines that need to be assigned to k locations available in the factory. The number of locations k and their positions are determined using Matlab as illustrated in Section 3.1. To formulate the model, the following assumptions are made.

3.2.1 Model assumptions:

1. Demand for each product is known deterministically and must be satisfied.
2. There is an operation sequence for each product.
3. Each operation can be performed in different types of machines and possibly with varying times of processing.

4. Machines are capable of performing various operations of different products at the same time.
5. There is a constant cost for a machine ($). This cost is incurred as an overhead value and does not depend on the utilization of the machine. This cost is expressed in monetary terms.
6. Each machine has a limited capacity (hrs).
7. The variable cost of machines is dependent on the assigned workload. The variable cost of machines is shown in monetary terms per unit time ($/hr).
8. The cost of carrying items between two locations is proportional to the number of carried products. Both inter- and intra-cell material handling costs are linearly proportional to the distance between the locations of the machines. Gaps between the locations are expressed in units of length.
9. All machines have the same dimension. Therefore, any machine can be assigned to any location. However, only one machine can be attached to a location.
10. The maximum number of cells and the minimum and the maximum number of machines in cells are assumed to be known in advance.
11. Positions and shapes of the cells are not predetermined.
12. Splitting of lots between two machines of same or different types is allowed.

3.2.2 Indexing setting:

p: index for product types.

r: index for operations.

c, d: indices for cells.

k, l: indices for locations.

i, j: indices for machine types.

3.2.3 Parameters:

P: number of product types to be produced.

N: Maximum number of cells.

R_p: Number of operations for product type p.

K: number of locations in the shop floor.

M: number of machine types.

E_p: Inter-Cellular material handling cost per product type p, per unit distance.

A_p: Intra-cellular material handling cost per product type p, per unit distance.

D_p: Demand for product type p.

λ_{kl}: Distance between location k and l.

δ_i: Installation cost of machine type i.

γ_i: Purchasing cost of machine type i.

β_i: Overhead cost of machine type i.

μ_i: Unit time variable cost of machine type i.

U: the maximum number of machines that can be assigned to a manufacturing cell.

L: The minimum number of machines that can be assigned to a manufacturing cell.

π_{pri}: each product p can perform Processing time of r^{th} operation of product type p, on machine type i.

C_i: Capacity of machine type i.

α_{pri}: 1, if r^{th} operation of the product type p can be processed by machine type i, 0, otherwise.

3.2.4 Decision variable:

x_{cki}: 1, if a machine of type i is placed on location k and assigned to cell c, 0, otherwise.

w_{prcki}: number of products of type *p*, processed in operation r on machine type *i* which is assigned to location *k* cell *c*.

$w_{prcdklij}$: Number of products of type *p*, processed by operation *r*, on machine type *i*, located in location *k* which is assigned to cell *c* and moved to be processed by operation *r*+1, on machine type *j*, located in location l which is assigned to cell *d*.

Q_i= total number of machines of type *i* added to the layout.

3.2.5 Objective Function

$$\text{Min } z= \sum_{p=1}^{P}\sum_{r=1}^{R_p-1}\sum_{c=1}^{N}\sum_{d=1}^{N}\sum_{k=1}^{K}\sum_{l=1}^{K}\sum_{i=1}^{M}\sum_{j=1}^{M} w_{prcdklij} \times \lambda_{kl} \times E_p \quad (1)$$
$$+ \sum_{p=1}^{P}\sum_{r=1}^{R_p-1}\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{l=1}^{K}\sum_{i=1}^{M}\sum_{j=1}^{M} w_{prcdklij} \times \lambda_{kl} \times A_p$$
$$+\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} x_{cki}\ \beta_i$$
$$+\sum_{p=1}^{P}\sum_{r=1}^{R_p-1}\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} w_{prcki} \times \pi_{pri} \times \mu_i$$
$$+\sum_{i=1}^{M} Q_i \times \gamma_i$$
$$+ \sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} x_{cki} \times \delta_i$$

Subject to the following constraints :

$$w_{prcki} \le x_{cki} \times \alpha_{pri} \times D_p \qquad \forall p,r,c,k,i \quad (2)$$

$$\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} w_{prcki} = D_p \qquad \forall\ p,r \quad (3)$$

$$\sum_{c=1}^{N}\sum_{i=1}^{M} x_{cki} \le 1 \qquad \forall\ k \quad (4)$$

$$\sum_{k=1}^{K}\sum_{i=1}^{M} x_{cki} \le U \qquad \forall\ c \quad (5)$$

$$\sum_{k=1}^{K}\sum_{i=1}^{M} x_{cki} \ge L \qquad \forall\ c \quad (6)$$

$$\sum_{p=1}^{P}\sum_{r=1}^{R_p}\sum_{c=1}^{N} w_{prcki} \times \pi_{pri} \le C_i \qquad \forall\ k,i \quad (7)$$

$$\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} w_{prcdklij} = w_{p,r+1,dlij} \qquad \forall\ p,d,l,j,t,r=1,\ldots, R_p-1 \quad (8)$$

$$\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} w_{prcdklij} = w_{prcki} \qquad \forall\ p,c,k,i,t,r=1,\ldots\ldots, R_p-1 \quad (9)$$

$$\sum_{c=1}^{N}\sum_{k=1}^{K} x_{cki} = Q_i \qquad \forall\ i \quad (10)$$

$$x_{cki} \in \{0,1\} \quad (11)$$

$$w_{prcki}, w_{prcdklij} \geq 0 \text{ and integer} \quad (12)$$

The objective function consists of six terms that aim at minimizing the total production cost. The first term is the inter-cellular material handling cost. This cost is incurred if consecutive operations on a part are performed in different cells. In that case, an inter-cellular material handling cost needs to be added to transfer the part from cell *c* to cell d where $c \neq d$. An intra-cellular material handling cost (second term) is incurred to account for the material handling cost to move parts within the same cell if two consecutive operations are performed on a part on two different machines in that cell. The third term is fixed overhead cost which is a constant cost for a machine and does not depend on the utilization of the machine. The fourth term is operating cost that is dependent on the assigned workload. The last two terms represent the cost of purchasing the machine and its installation cost respectively.

The objective function is subject to constraints illustrated in (2)- (12). The first constraint (2) ensures that an operation for a given product type can only be processed in a given location if a machine that is capable of carrying out this operation is assigned to the location. It also guarantees that the total number of processed parts does not exceed the demand for the product. Second constraint (3) states that the total number of products produced (X_{cki}) must be equal to the demand. Third constraint (4) makes sure that not more than one machine can be assigned to a location, and a location can only be allocated to one cell. Fourth and Fifth constraints (5 and 6) impose an upper and lower limit on number of cells in a layout. Machine capacity constraint (sixth constraint) is set using (7) by stating that the total processing time of all operations on a machine cannot exceed its capacity. Constraints 7 and 8 (9 and 10) ensure that order of processing is met. Constraint 7 (9) makes certain that the total number of the incoming product from all other locations to a location for its next operation is equal to the number of products, which will receive their next operation in the given location. While (10) guarantees that the total number of moving products from a given location to any location for its next operation is equal to the number of products, which are receiving their current operation in the given location. Constraint nine calculates the total number of machines in the layout by summing how many locations contain that machine type. Last two constraints define which variables are binary and which are integers.

3.3. Defining the distance, λ_{kl}, matrix

To define the distance matrix between different locations, k and l, a MATLAB code was used to model the logic and generate the matrix for each of the proposed layouts Circular (C) and traditional (R). For the sake of comparison, both layouts share the same input such as the size of the area being used to distribute machines ($B_x \times B_y$), Dimensions of machines ($L \times W$), and the space between machines, which is referred to as the aisle space (AL). Those parameters were considered to be the input in order to compute a matrix of possible locations to place machines based on distances between them.

A traditional open field layout seeks to arrange machines in a rectangular shape as shown in (Figure 3.5). The aisle space is assumed to be wide enough to allow for AGVs to travel in both directions between locations.

To determine the distance matrix λ_{kl}

- The number of machines in each row (n) is equal to B_x divided by the summation of machine's width and aisle space.

$$n = \frac{B_x}{w + Al} \tag{13}$$

- The number of machines in each column (p) is equal to B_y divided by the summation of machine's length and aisle space.

$$p = \frac{B_y}{L + Al} \tag{14}$$

- The total number of possible locations that can be utilized in the shape is equal to multiplying (p) by (n).

$$T = p \times n \tag{15}$$

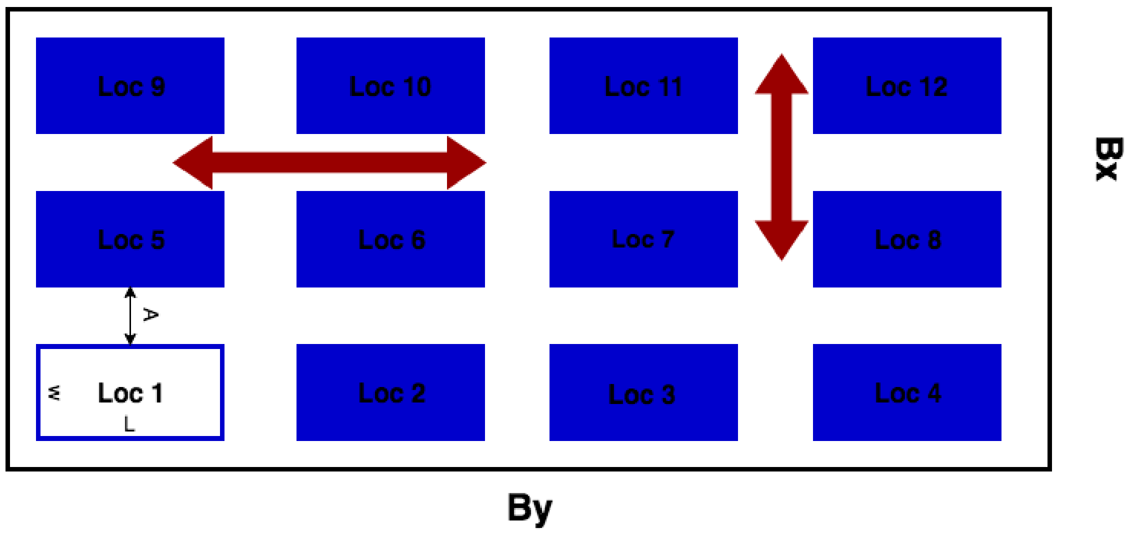

Figure 3.5: Traditional layout

The next step is to label each location by its coordinates (*x*,*y*). Each coordinate was calculated separately since it will be an asymmetric shape, and the aisle spaces will be straight lines. The following steps show an illustration of the computation process.

- For each row, the first location starts with (*x*=0). Then, in order to locate the start of next location, an increment which is equal to the parameter that *Bx* was divided by (the summation of machine's width and aisle space) has to be developed. This step can go on until the next location is greater or equal to *Bx* which has to be rejected, and hence stop incrementing.
- The same steps were applied to each column except that *By* is used instead of *Bx*, and the increment is equal to the summation of Machine's length and aisle space.

Figure (3.6) is a summary of the steps mentioned above.

The idea behind labeling each location is to calculate distances between each location, which should be summarized in a distance matrix. The way of calculating the distance between any two locations, which is from (x_i, y_i) to (x_j, y_j), is by using the following equation:

$$\lambda_{kl} = |x_i - x_j| + |y_i - y_j| \tag{16}$$

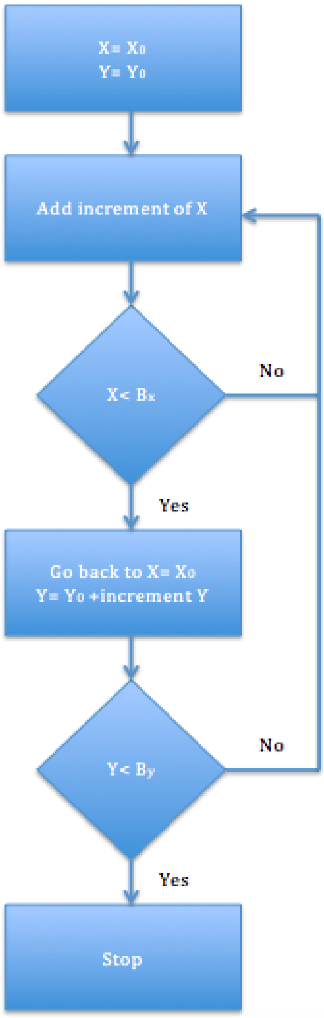

Figure 3.6: decision diagram for developing machines' locations

This matrix is being used as an input for the optimization model in order to place machines in the identified locations.

In traditional layout, length and width of floor space maybe different which is not the case for a circular layout. For a circular layout, it is assumed that the floor space is square in shape. To define the coordinates of the locations and calculate λ_{kl} for circular layout, length of the space is assumed to be equal to the smallest dimension in a traditional layout i.e. minimum of (*Bx* or By).

- Next, set specific parameters such as the r_0, machine dimension (length (l), width (w)), and aisle space (Al). r_0 is calculated so that the maximum number of machines can be incorporated in a given area as explained in section 3.2.
- Number of loops is calculated as follows:

$$\# \ of \ Loops = \frac{\frac{Min\ (Bx, By)}{2} - r_0}{l + Al} \tag{17}$$

- For the first loop, machines are laid around the inner perimeter of radius r_0. The number of machines in the first loop is calculated as:

$$\# \ of \ Machines \ (n) = \frac{2\pi r_0}{w + Al} \tag{18}$$

The term (w+Al) represents the width of the machine and the aisle space since machines have to be separated by a certain amount of space to allow any material handling system to travel efficiently.

- The increment of θ in the first loop is then defined as:

$$Inc\ \theta = \frac{360}{n} \tag{19}$$

This increment can be referred to as a sector. Sectors represent identical parts of the circle in which the aisle space can go all the way from the center to the end of last calculated loop. These sectors may, or may not, be considered cells, depending on the output of calculations.

By pairing it up with r_0, the result for each location can be determined as a magnitude of ($\theta_{i-1} + Inc\ \theta,\ r_0$).

- Then, the increment of r is calculated in order to determine the radius of next loop as follows:

$$r_i = r_0 + [i \times (L + Al)] \tag{20}$$

- Repeat the same steps, as in the first loop, to find the number of machines in the new loop, followed by the same succeeding steps as stated above.
- The process is repeated until the radius (r_i) added to (L +Al) is greater than half of either Bx or By which is smaller.
- The ability to calculate the distance matrix between each location, (from Location (s) to Location (m)), will depend on the orientation of the layout. Several logic conditions are added to determine how the AGVs will move.
    - If the location (s) is the same as the location (m), then the distance is zero.

Else AGV can travel through inner loop or through outer loop as seen in figure (figure 3.7).

- e.g. in case of horizontal alignment, and locations (s) and (m) are in different circles (Figure3.7) , and radius of location s (r_s) is greater than radius of location m (r_m), and AGV is travelling along inner loop then λ will be calculated as follows:

$$\lambda = |r_s - r_m| + 2\pi \times (r_s) \times \frac{min(|\theta_s - \theta_m|, |360 - \theta_s - \theta_m|)}{360} \qquad (21)$$

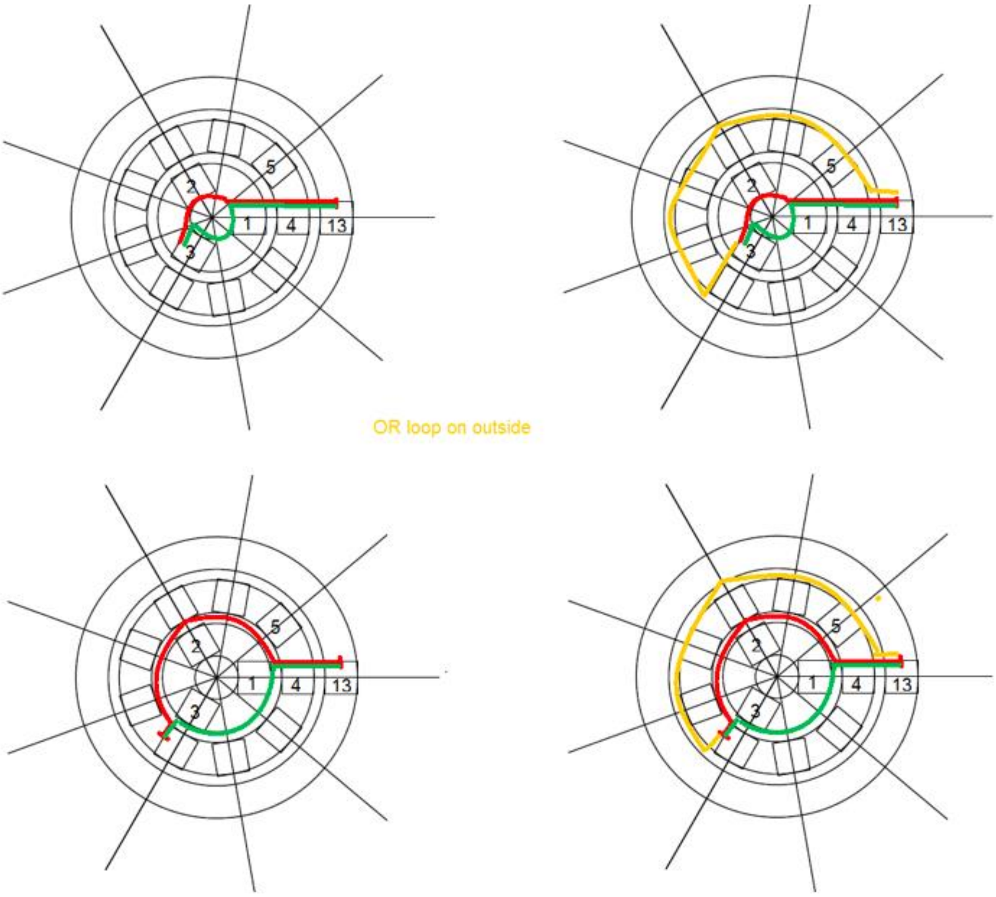

Figure 3.7: Various travel routes along inner loop or outer loop

A similar approach is used to model the rest of the scenarios for inner and outer loops for both horizontal and inner alignment. Matlab code is added in appendix E for further details.

Chapter 4. Results and Analysis

4.1. Model validation

To validate the model, results are compared with a numerical example from the literature. The proposed model was extended to include time domain, installation δ_i and uninstallation cost θ_i of machines, to be able to compare the results with Baryam and Sahin [3] solution. An additional constraint (31) was added to calculate the number of added machines starting from period 2, constraints (33) and (34) relate decision variables x and y, former constraint related to installation and later to uninstallation. The rest of the model is the same.

$$\text{Min } z= \sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{r=1}^{R_p-1}\sum_{c=1}^{N}\sum_{d=1}^{N}\sum_{k=1}^{K}\sum_{l=1}^{K}\sum_{i=1}^{M}\sum_{j=1}^{M} w_{prcdklijt} \times \lambda_{kl} \times E_p \tag{22}$$
$$+ \sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{r=1}^{R_p-1}\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{l=1}^{K}\sum_{i=1}^{M}\sum_{j=1}^{M} w_{prcdklijt} \times \lambda_{kl} \times A_p$$
$$+ \sum_{t=2}^{T}\sum_{k=1}^{K}\sum_{i=1}^{M} (y_{kit} \times \delta_i) + \sum_{t=2}^{T}\sum_{k=1}^{K}\sum_{i=1}^{M} (y'_{kit} \times \theta_i)$$
$$+\sum_{t=1}^{T}\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} x_{ckit} \times \beta_i$$
$$+\sum_{t=1}^{T}\sum_{p=1}^{p}\sum_{r=1}^{R_p-1}\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} w_{prckit} \times \pi_{pri} \times \mu_i$$
$$+ \sum_{t=1}^{T}\sum_{i=1}^{M} Q_{it}\, \gamma_i + \sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} x_{cki1} \times \delta_i$$

Subject to the following constraints :

$w_{prckit} \leq x_{ckit} \times \alpha_{pri} \times D_{pt}$	∀p,r,c,k,i,t	(23)
$\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} w_{prckit} = D_{pt}$	∀ p,r,t	(24)
$\sum_{c=1}^{N}\sum_{i=1}^{M} x_{ckit} \leq 1$	∀ k,t	(25)
$\sum_{k=1}^{K}\sum_{i=1}^{M} x_{ckit} \leq U$	∀ c,t	(26)
$\sum_{k=1}^{K}\sum_{i=1}^{M} x_{ckit} \geq L$	∀ c,t	(27)
$\sum_{p=1}^{P}\sum_{r=1}^{R_p}\sum_{c=1}^{N} w_{prcdklijt} \times \pi_{pri} \leq C_i$	∀ k,i,t	(28)
$\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} w_{prcdklijt} = w_{p,r+1,dlijt}$	∀ p,d,l,j,t,r=1,…., $R_p - 1$	(29)
$\sum_{c=1}^{N}\sum_{k=1}^{K}\sum_{i=1}^{M} w_{prcdklijt} = w_{prckit}$	∀ p,c,k,i,t,r,=1,……, $R_p - 1$	(30)
$\sum_{c=1}^{N}\sum_{k=1}^{K} x_{cki,t+1} - \sum_{c=1}^{N}\sum_{k=1}^{K} x_{ckit} = Q_{i,t+1}$	∀ i	(31)
$\sum_{c=1}^{N}\sum_{k=1}^{K} x_{cki,1} = Q_{i,1}$	∀ i	(32)
$(1 - \sum_{c=1}^{N} x_{ckit}) \times \sum_{c=1}^{N} x_{cki,t+1} = y_{ki,t+1}$	∀k,i,t=1,…..,T-1	(33)
$\sum_{c=1}^{N} x_{ckit} \times (1 - \sum_{c=1}^{N} x_{cki,t+1}) = y'_{ki,t+1}$	∀ k,i,t=1,….., T-1	(34)
$x_{ckit}, y_{kit}, y'_{kit} \in \{0,1\}$		(35)
$w_{prckit}, w_{prcdklijt}, Q_{it} \geq 0$ *and integer*		(36)

Constraints (33) and (34) include multiplications of decision variables, violating linearity of the model. The same procedure, followed by Baryam and Sahin [3], was followed to linearize the model. A numerical example, provided by Baryam and Sahin [3], was used for validation. It consists of two part types, three operations for each part, and three machine types. Figure 4.1 shows the available locations for the machine assignment. Maximum number of machines in a cell was constrained between 1 and 3, and 2 cells must be formed.

L1	L2
L3	L4
L5	

Figure 4.1: 5 Machine locations L1-L5

The distance matrix of locations λ_{kl} is calculated, assuming unit distance between the machines as given in Table 4.1. The inter-cell material handling cost was assumed to be \$50/m, and intracellular material handling cost to be \$5/m. All the machines are assumed to have a fixed size with L and H equal to 1.

Table 4.1: distance matrix of locations λ_{kl}

	l=1	**l=2**	**l=3**	**l=4**	**l=5**
k=1	0	1	1	2	2
k=2	1	0	2	1	3
k=3	1	2	0	1	1
k=4	2	1	1	0	2
k=5	2	3	1	2	0

Machine parameters, including purchasing, overhead, installation, uninstallation, variable costs and machine capacity, ae given in Table 4.2. Table 4.3 shows the routing sequence of each product and the processing time it takes to perform this operation on that machine. (-) Indicates that this operation can’t be performed on that specific machine type. Most operations can be performed on more than one machine which allows for load splitting rather than machine duplication if this will minimize cost in case machine capacity is exceeded. The demand for the product can differ from1 period to the other as indicated in Table 4.4.

Table 4.2: Purchasing cost, Overhead Cost, Installation Cost, Uninstallation Cost, Unit variable Cost, Capacity of machine

Machine	$\boldsymbol{\gamma_i}$**($)**	$\boldsymbol{\beta_i}$**($)**	$\boldsymbol{\delta_i}$**($)**	$\boldsymbol{\theta_i}$**($)**	$\boldsymbol{\mu_i}$**($/h)**	$\boldsymbol{C_i}$**(h)**
i=1	18000	1800	450	450	9	500
i=2	15000	1500	375	375	7	500
i=3	16000	1600	400	400	6	500

Table 4.3: π_{pri} Processing time and routing of operations

Product P=1	**Processing time for operations sequence**		
	R=1	R=2	R=3
Machine i=1	0.54	0.79	-
Machine i=2	-	0.53	-
Machine i=3	0.77	-	0.33
Product P=2	Processing time for operations sequence		
	R=1	R=2	R=3
Machine i=1	-	0.8	-
Machine i=2	0.45	-	0.76
Machine i=3	-	0.91	0.80

Table 4.4: Product Demand (D_{pt}) in units of product type P at period t

$\boldsymbol{D_{pt}}$	**Product P=1**	**Product P=2**
Time Period t=1	400	300
Time Period t=2	500	200

Model is coded in Lingo software (available in Appendix D). The MILP was solved using Branch-and-Bound method using Lingo, and a Global Optimum solution was found with an objective function value of $103,434 which matches solution of Baryam and Sahin [3]. Figure 4.2 shows the results and method utilized. Baryam and Sahin [3] used simulated annealing SA to find an integer solution for the problem.

```
Global optimal solution found.
Objective value:                                  103434.0
Objective bound:                                  103434.0
Infeasibilities:                                  0.000000
Extended solver steps:                              153718
Total solver iterations:                          13102403
Elapsed runtime seconds:                           2599.20

Model Class:                                          MILP

Total variables:                11288
Nonlinear variables:                0
Integer variables:              11280

Total constraints:               1087
Nonlinear constraints:              0

Total nonzeros:                 29232
Nonlinear nonzeros:                 0
```

Figure 4.2: Lingo Software optimal solution

Figures 4.3 and 4.4 compare the optimal solution obtained by model using Branch and Bound solution with that of Baryam and Sahin [3]. The machine allocation is identical in both cases, forming two clusters with 2 machines in each cell. The cell assignment is vertical in the optimal solution obtained, while it is horizontal in Baryam and Sahin [3] solution, but this will not affect the objective function value as illustrated by product routing in Figure 4.4.

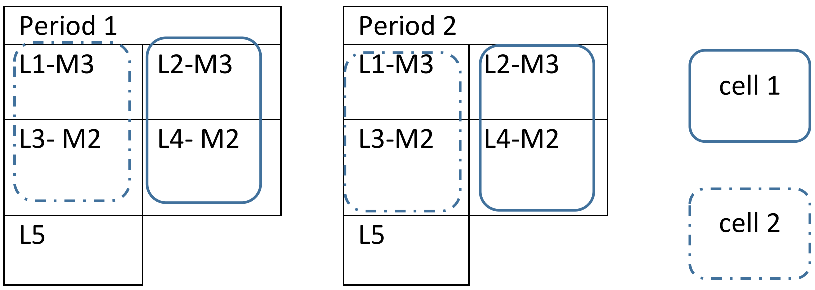

Figure 4.3: Machine assignments (a) Period 1,(b) Period 2 (optimal solution)

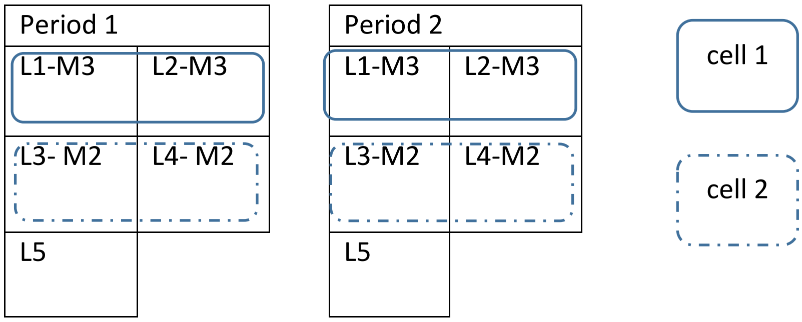

Figure 4.4: Machine assignments (a) Period 1,(b) Period 2 (Baryam and Sahin solution [3])

Figure 4.5 reveals that products are split between cells initially then s; it goes from one process to the following one; it stays within the same cell to minimize the intercellular material handling cost. Product splitting can also be seen. Splitting occurs in case a machine cannot accommodate all work units without exceeding its capacity and it is cheaper to use an existing machine that is not fully utilized rather than duplicating a machine that would lead to an additional cost resulting from purchasing additional equipment. It is clear from the total quantity of products obtained at each operation that the demand for that product at that time period is met.

					Product 1			***Product 2***		
	cell	***loc***	***Mach***		*r=1*	*r=2*	*r=3*	*r=1*	*r=2*	*r=3*
	1	4	2					265		
Period 1	1	2	3						265	265
	2	3	2			400		35		
	2	1	3		400		400		35	35
				Total	*400*	*400*	*400*	*300*	*300*	*300*
					Product 1			***Product 2***		
	cell	***loc***	***Mach***		*r=1*	*r=2*	*r=3*	*r=1*	*r=2*	*r=3*
	1	2	3		280		280		112	112
Period 2	1	4	2			280		112		
	2	1	3		220		220		88	88
	2	3	2			220		88		
				Total	*500*	*500*	*500*	*200*	*200*	*200*

Figure 4.5: Product routing during periods 1 and 2

4.2. Clustering behavior for various layouts

After formulating and validating the model, it was necessary to visualize the effect of various layouts on cell clustering and the cost before proceeding further. A simple scenario is considered for which the cell groupings can be verified numerically. The operation sequence is only considered in the model in this case. A factory with 8 machines is utilized to produce 10 products. Each product has its own routing arrangement, and the total number of routing for all products is the same, which are three. The product routings are shown in Table 4.5.

Table 4.5: Product routing process

Product #	**Operation 1**	**Operation 2**	**Operation 3**
P1	M2	M5	M7
P2	M3	M4	M8
P3	M1	M3	M6
P4	M2	M5	M7
P5	M3	M4	M8
P6	M2	M5	M7
P7	M1	M5	M6
P8	M2	M5	M7
P9	M3	M4	M8
P10	M2	M3	M8

Another way to display the above table is by illustrating the product's routing arrangement as per the machines used (Table 4.6). Table 4.6 can be applied to illustrate the relationship between each product and the required machines.

Table 4.6: Product routing process 2

	P1	***P2***	***P3***	***P4***	***P5***	***P6***	***P7***	***P8***	***P9***	***P10***
M5	1			1		1	1	1		
M7	1			1		1	1	1		
M2	1			1		1		1		1
M3		1	1		1				1	1
M8		1			1				1	1
M4		1			1				1	
M1			1				1			
M6			1							

The demand for each product type is assumed to be equal to a hundred items. The number of items can be introduced to the above table to illustrate the transformation process as given in Table 4.7.

Table 4.7 Product routing process – considering product demand

	P1	***P2***	***P3***	***P4***	***P5***	***P6***	***P7***	***P8***	***P9***	***P10***
M5	100			100		100	100	100		
M7	100			100		100	100	100		
M2	100			100		100		100		100
M3		100	100		100				100	100
M8		100			100				100	100
M4		100			100				100	
M1			100				100			
M6			100							

The "from-to" matrix is used to organize travelling products between machines. For example machine 1 has 100 units to send to machine 3 and 100 units to send to machine 5; machine 3 also has to send 300 units to machine 4 and 100 units to machine 6 and machine 8. Computing the same concept to the rest of machines results in the following table (Table 4.8).

Table 4.8: Travelling products between machines

	M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**
M1			100		100			
M2			100		400			
M3				300		100		100
M4								300
M5						100	400	
M6								
M7								
M8								

The above table shows a strong relationship between machine 2 and machine 5, as well as between machine 5 and machine 7. As a result, these three machines should be placed next to each other in a cell. The following figure explains the sequence of these three machines.

Figure 4.6: Sequence of machines with the strongest relationship

Another relationship can be detected between machine 3 and machine 4, and between machine 4 and machine 8, which can be grouped into a second cell. As shown in Figure 4.7, both cells are formed based on the total number of items travelling between them regardless of the type or sequence of routing.

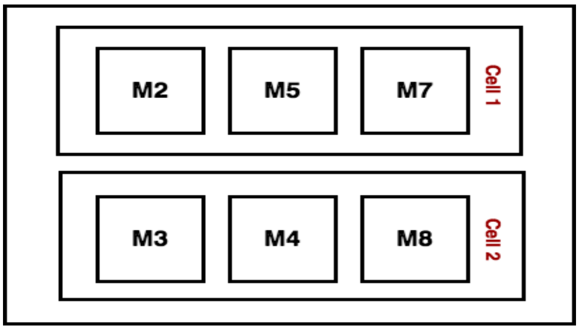

Figure 4.7: Layout of machines within cells

The matrix shows that some machines have no relationships. Those machines could be placed anywhere, but not too close to each other.

To group the machines and product types, the rank order clustering technique is applied to the part-machine incidence matrix illustrated in Table 4.8 to determine the logical part families and machine groups, shown in Table 4.5.

Table 4.9 demonstrates that when forming cells, some products can be grouped as part of a family despite their routing sequences, provided they use the same machines. For example Products 1, 4, 6 and 8 can be considered as a part family since they can be manufactured in the same cell, using only machines inside this cell. A second part family consisting of Products 2, 5 and 9 can be considered, because they are being processed in the same cell as well. The transfer of products within the cell is referred to as “intracellular”.

Table 4.9: clustering technique

	P1	P4	P6	P8	P7	P10	P2	P5	P9	P3
M5	1	1	1	1	1					
M7	1	1	1	1	1					
M2	1	1	1	1		1				
M1					1					1
M3						1	1	1	1	1
M8						1	1	1	1	
M4							1	1	1	
M6										1

Products 7, 10 and 3 would involve intercellular movements, i.e., material handling between cells. To produce Product 7, it would need to move from Machine 5 in Cell 1 to Machine 7 in the same cell and finally across cells to Machine 1. Product 10 is produced starting with Machine 2 in Cell 1, then moving it consecutively to Machine 3 and Machine 3 in Cell 2. Product 3 is routed through Machine 1, located in a given cell, before being moved to Machine 3 in Cell 2, and then transferred again to Machine 6 in another cell (Table 4.9). Machines 1 and 6 are to be located in such a manner that minimizes material handling movements.

The basic idea is where to place each machine in order to minimize total costs, especially the travelling costs. Different scenarios are tested where space areas, shapes and other criteria vary for each case. Each of these scenarios is solved in a bid to determine that with the optimum performance. Comparisons are mainly drawn in terms of the performance between different shapes. For all tested cases, the unit cost and other inputs, apart from shape related variables, will remain the same. The following assumptions apply.

Demand for each product = 300 units.

Number of locations = number of machines = 8 locations.

Intercellular material handling cost = $100

Intracellular material handling cost= $1

Overhead costs of each machine type = $1400

Unit time variable cost of each machine = 7 periods

Capacity of each machine = 5000 units

The total area here will vary because each area has some specifications such as applying aisle space or not, but the changes are made so that the facility can accumulate eight machines in each case at the minimum possible area.

4.2.1. Rectangular shape without aisle space. The scenario here presupposes that the distribution of machines is rectangular shaped, and the aisle space is being neglected. This case is only theoretical as it will be impractical in reality; however, for the sake of this study, it is still necessary to compare this scenario with that where aisle spaces are included. The following figure demonstrates the case.

Figure 4.8 indicates four columns and two rows, which result in eight locations for machines to be placed. Each machine dimension is $(1 \times 1)\ m^2$, while the total floor area is 8 m^2.

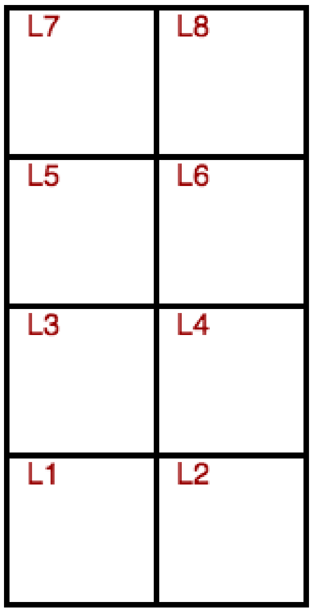

Figure 4.8: Rectangular shape distribution of machine without aisle space

Equation 16 can be applied in computing the distance matrix as previously explained in Section 3.2. Nevertheless, all aisle spaces were considered to be zero. The result is summarized in the following matrix.

	L1	L2	L3	L4	L5	L6	L7	L8
L1	0	1	1	2	2	3	3	4
L2	1	0	2	1	3	2	4	3
L3	1	2	0	1	1	2	2	3
L4	2	1	1	0	2	1	3	2
L5	2	3	1	2	0	1	1	2
L6	3	2	2	1	1	0	2	1
L7	3	4	2	3	1	2	0	1
L8	4	3	3	2	2	1	1	0

Figure 4.9: Distance matrix for rectangular shape distribution of machine without aisle space

This matrix is used as an input to calculate the total cost for this scenario by applying the LINGO code, and the result obtained is $294600. The output is as follows:

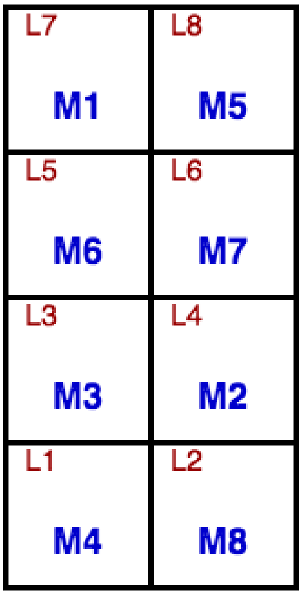

Figure 4.10: Output layout: allocation of machines to designated locations in rectangular shape without aisle space

As it displayed in the Figure 4.10, Machine 2, 7 and 5 can form a vertical cell, while Machine 3, 4 and 8 form an L-shaped cell. The other machines are placed at optimal locations.

4.2.2. Rectangular shape with aisle space. The rectangular shape with aisle space is similar to previous case without aisle (Section 4.2.1); however, in this instance, the aisle space is added, increasing the area to accommodate all conditions. As stated before, the rectangular shape has four rows and two columns. Each machine has a dimension of $(1.5 \times 0.75)\ m^2$. The facility area is 24.75 m2, and the aisle space here is assumed to be half a meter (0.5 m), which in the minimum space for products to travel between machines. The following (Figure 4.11) illustrates the layout for this case.

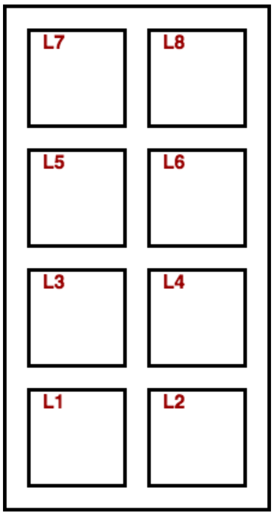

Figure 4.11 Rectangular shape layout with aisle space

The distance matrix for this case is obtained by running the distance code used by MATLAB with aisle space. The output is as follows:

	L1	L2	L3	L4	L5	L6	L7	L8
L1	0	2	1.3	3.3	2.5	4.5	3.8	5.8
L2	2	0	0.8	1.3	0.5	2.5	1.8	3.8
L3	1.3	0.8	0	2	1.3	3.3	2.5	4.5
L4	3.3	1.3	2	0	0.8	1.3	0.5	2.5
L5	2.5	0.5	1.3	0.8	0	2	1.3	3.3
L6	4.5	2.5	3.3	1.3	2	0	0.8	1.3
L7	3.8	1.8	2.5	0.5	1.3	0.8	0	2
L8	5.8	3.8	4.5	2.5	3.3	1.3	2	0

Figure 4.12: Distance matrix for rectangular shape layout with aisle space

The distance matrix shown in Figure 4.12 is used in the LONGO code to compute the total cost, given as $264525.0. The output layout is listed in Figure 4.8 below.

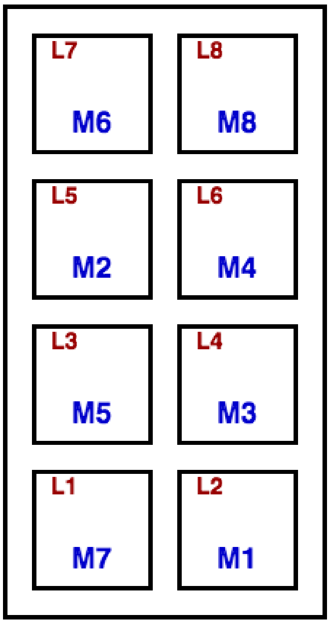

Figure 4.13: Output layout: allocation of machines to designated locations in rectangular shape with aisle space

As in the previous rectangular layout, each machine is assigned to separate locations. The distribution of individual machines is different from the layout without aisle space. However, the shape and orientation of cells for the same group of machines is similar for Machine 2, 5 and 7; this group of machines is contained in a vertical cell (Figure 4.13). Unlike the output layout without aisle space, Machine 3, 4 and 8 are also grouped in a vertical cell. The total cost is less than the previous layout.

4.2.3. Circular layout with horizontally oriented machines. In this case, the layout is circular, and lengths of machines are attached to the inner circumference. This means that the number of locations in each annular section is limited, and the total number of machines to fit each annular section is calculated by dividing the circumference by the longest dimension given for machines. The same machine size, as in the case of the rectangular layout, is considered, which is $(1.5 \times 0.75)\ m^2$. The facility area and aisle space are also similar to that for the rectangular layout and set to be 24.75 m2 and 0.5 respectively. The inner radius r_0 is 0.7 m.

A MATLAB code is used to compute the distance matrix, given as follows:

	L1	L2	L3	L4	L5	L6	L7	L8
L1	0	2.2	0	2	2.7	3.4	2.7	2
L2	2.2	0	3.4	2.7	2	0	2	2.7
L3	0	3.4	0	2	4.1	6.1	4.1	2
L4	2	2.7	2	0	2	4.1	6.1	4.1
L5	2.7	2	4.1	2	0	2	4.1	6.1
L6	3.4	0	6.1	4.1	2	0	2	4.1
L7	2.7	2	4.1	6.1	4.1	2	0	2
L8	2	2.7	2	4.1	6.1	4.1	2	0

Figure 4.14: Distance matrix for circular shape layout with horizontal oriented machines

Figure 4.15 is an illustration of each location found, as calculated in the code.

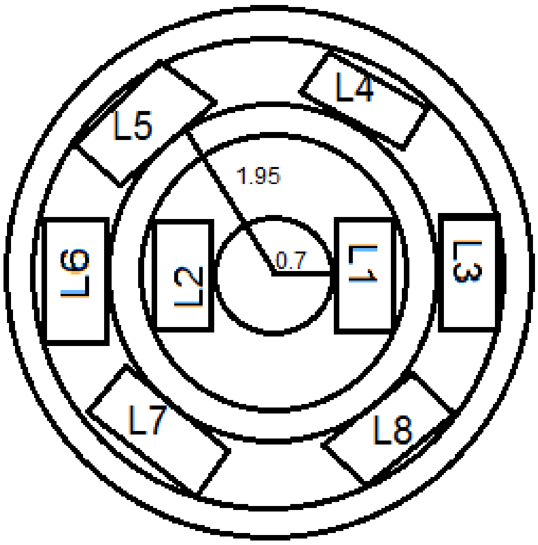

Figure 4.15 Circular shape layout for horizontal oriented machines

Two layers are created. Due to the size of the inner circle, the first (inner) layer is assigned only two locations, while the rest of the locations are housed within the second layer (Figure 4.15)

The output of the distance matrix for this circular shaped layout serves as an input to the LINGO code used to calculate the total cost. This is $264741.7. Figure 4.16, below, summarizes the output of machine locations.

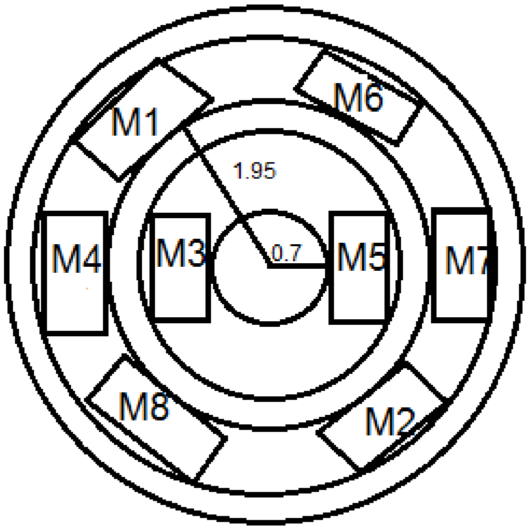

Figure 4.16 Output layout: allocation of machines to designated locations in circular shape space for horizontal oriented machines

In the circular shaped layout for horizontal oriented machines, it is possible for cells to overlap across locations in different circulalr (annular) spaces. Some machines may be in the inner circle (inner layer), while others belonging to the same cell may be assigned to locations in the outer layer or the next circle. According to the previous design, Machine 2, 5 and 7 are grouped in one cell, whereas Machine 3, 4 and 8 are grouped in a separate cell. However, in this layout, Machine 5 is situated in the inner layer, while Machine 2 and 7 are in the outer layer. Machine 2 and 7 are located close to and behind Machine 5 (Figure 4.16). In a somewhat likewise pattern, Machine 3 is located in the inner layer (inner circle); at the same time, Machine 4 and 8 are situated behind and adjacent to Machine 3, in the next and outer layer (Figure 4.16). In both configurations displayed in the circular shaped layout, a reduction in distance between machines is feasible.

4.2.4. Circular layout with vertically oriented machines. The type of layout is analogous to the previously described circular shaped layout with horizontal oriented machines; the difference is that the machines are oriented vertically, i.e., rotated so that the shorter dimension, which is the width, is attached to the circumference of the circle (Figure 4.17). As with the preceding case (circular shaped layout described in Section 4.1.3), all the inputs are the same except that the inner radius r0 is 1.6 m, and the facility area is 40.7 m.

The output distance matrix of the MATLAB code for circular layout is as follows.

	L1	L2	L3	L4	L5	L6	L7	L8
L1	0	3.3	4.5	5.8	7	5.8	4.5	3.3
L2	3.3	0	3.3	4.5	5.8	7	5.8	4.5
L3	4.5	3.3	0	3.3	4.5	5.8	7	5.8
L4	5.8	4.5	3.3	0	3.3	4.5	5.8	7
L5	7	5.8	4.5	3.3	0	3.3	4.5	5.8
L6	5.8	7	5.8	4.5	3.3	0	3.3	4.5
L7	4.5	5.8	7	5.8	4.5	3.3	0	3.3
L8	3.3	4.5	5.8	7	5.8	4.5	3.3	0

Figure 4.17 Distance matrix for circular shape layout with vertically oriented machines

According to the output from the distance matrix, the distribution of locations is as in the Figure 4.18

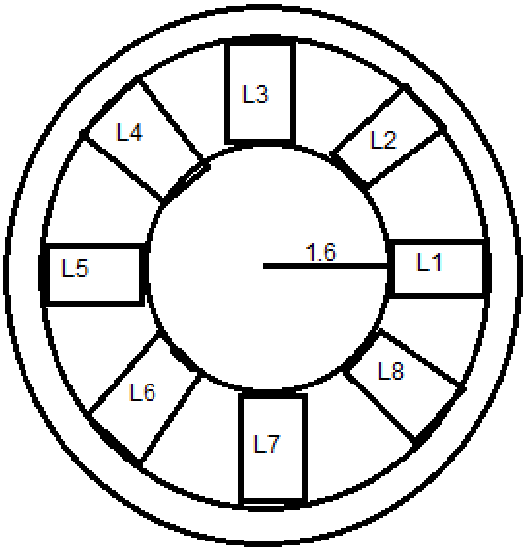

Figure 4.18: Circular shape layout for vertical oriented machines

As displayed in Figure 4.18, and unlike the circular shaped layout for horizontal oriented machines, there is only one layer with all the possible locations for machine distribution. Using the distance matrix as input in the LINGO code, the total cost is computed to be $512003.7, and the chart showing the machine distribution is given in Figure 4.20.

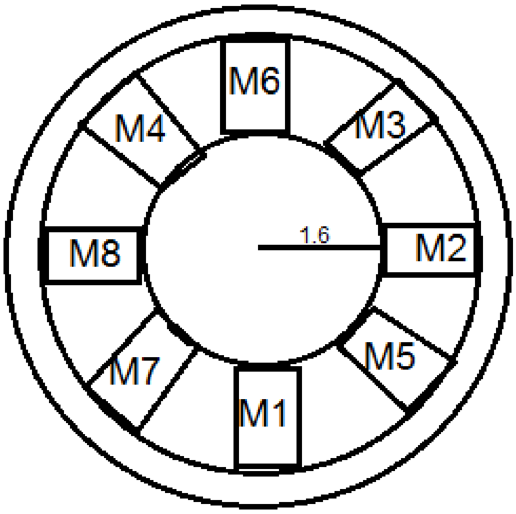

Figure 4.19: Output layout: allocation of machines to designated locations in circular shape space for vertical oriented machines

Results reveal that, for all scenarios, Cases 4.2.2. (Rectangular shape with aisle space) and 4.2.3. (Circular layout with horizontally oriented machines) gave the best result in terms of minimizing the total cost. Additionally, they were the fastest in terms of the computation time. For this reason, those two cases will be investigated in more details under different scenarios. Note that the cost of the circular shaped layout with horizontal oriented machines (4.2.4) is $264,741.7, which is higher than that of the rectangular layouts.

4.3. Design of Experiments

The main objective of this research is to study the effectiveness of circular layout compared to the traditionally used rectangular layout, specifically in cases where it is feasible to have a squared shaped facility area. The idea is to determine which layout would be cost effective and efficient, especially as the complexity of the product increases. To achieve this design, experiments will be utilized to study the effect of the interaction of layout and product variety and complexity on production cost. The production cost is the response factor in the experiment. It is quantified using the LP model. To reduce the number of runs while considering the nonlinear behavior between factors and response, a Face Centered Composite Design (FCCD) was chosen as a method of analysis rather than a 3-level full factorial design. Four factors are examined in the study. The first factor studied is the types of products produced (P) which affects both the variety and quantity produced. If several products are produced, then there is a high variety in the production process as well as an increase in the total production quantity to be satisfied by the company. Such products may be similar or different, indicating a soft or hard product variety respectively. To capture that, the second factor examined was routing or number of operations. The larger this number, the more complex the product is and the higher the probability that there is less similarity between the produced products.

Table 4.10: Face centered composite experimental design

Run Order	*PtType*	*Blocks*	*Product*	*Routing*	*Machines*	Layout
1	1	1	4	2	10	C
2	1	1	4	4	20	R
3	0	1	7	3	15	R
4	-1	1	7	4	15	C
5	1	1	4	4	20	C
6	-1	1	7	3	15	C
7	1	1	10	2	20	R
8	0	1	7	3	15	R
9	-1	1	7	2	15	R
10	0	1	7	3	15	C
11	-1	1	10	3	15	C
12	-1	1	7	3	20	C
13	1	1	10	4	10	C
14	1	1	4	2	20	C
15	-1	1	7	2	15	C
16	1	1	10	4	20	R
17	1	1	4	4	10	R
18	0	1	7	3	15	C
19	0	1	7	3	15	R
20	1	1	10	2	10	C
21	0	1	7	3	15	C
22	0	1	7	3	15	C
23	0	1	7	3	15	R
24	-1	1	7	3	20	R
25	1	1	4	4	10	C
26	0	1	7	3	15	R
27	-1	1	10	3	15	R
28	0	1	7	3	15	R
29	0	1	7	3	15	C
30	1	1	10	2	20	C
31	1	1	10	4	10	R
32	-1	1	4	2	15	R
33	-1	1	4	2	15	C
34	-1	1	7	2	10	R
35	1	1	10	4	20	C
36	0	1	7	3	15	C
37	1	1	10	2	10	R
38	-1	1	7	2	10	C
39	1	1	4	2	20	R
40	1	1	4	2	10	R

In addition to that, as the number of machines required to produce the product vary, the harder the product variety is and the more distinct the processing of operations becomes. Another important aspect to be examined is the factory space and layout. The proposed circular layout is to be compared to the traditional rectangular one to determine how it interacts with other factors and influences cost. The first three factors are continuous variables, while the last is categorical rectangular layout-R versus circular layout-C). The effect of those variables on the total cost (calculated from the LP objective function value) is examined. The number of product types varied between 4 and 10, routing between 2 and 4 operations and number of locations between 10 and 20. Each experiment was replicated twice to account for variation in the processing time. A total of 40 runs in each replicate, with cube points equal to 16, center points in cube equal to 12 and axial points equal to 12. Table 4.10 illustrates the randomized 40 experiments to be studied.

A random number generator function is used to generate, π_{pri}, the processing time of r^{th} operation of product type p, on machine type i. A generic function in Matlab software, *random*, was used for that purpose. *Random* returns an array of random numbers chosen from a two- or three-parameter probability distribution with parameter values A, B (and C). Extreme values between 0 and 1 were generated using this distribution. For example, to generate run 1 with 4 product types, 2 operations routing and 10 machines, then Pi= round(random('ev',0,1,[10,8]) ,3), will generate 10 rows (10 machines) x 8 columns (4 products with 2 operations each) array with extreme values between 0 and 1 indicating the processing time. Table 4.11 shows that the output of the randomly generated function ran twice. Zero means that the operation cannot be performed by that machine. In example 1, to produce product 1, it must go through machine 8 for the first operation; however, for the second process, it can be processed on any of machines 1,2,3 and 9. The processing time will differ, depending on the machine used, as indicated in the table below.

Table 4.11: π_{pri} Processing time and routing of operations

Examle 1	*Product 1*		*Product 2*		*Product 3*		*Product 4*	
	r=1	**r=2**	**r=1**	**r=2**	**r=1**	**r=2**	**r=1**	**r=2**
Machine i=1	0	0.492	0.397	0.57	0.392	0	0.155	0
Machine i=2	0	0.524	0	0	0	0.787	0.303	0
Machine i=3	0	0.292	0	0	0.41	0.762	0.195	0.134
Machine i=4	0	0	0.9	0.291	0	0	0	0
Machine i=5	0	0	0.364	0	0	0	0	0.38
Machine i=6	0	0	0	0	0.001	0	0	0
Machine i=7	0	0	0.84	0.293	0.089	0	0.689	0
Machine i=8	0.805	0	0	0	0	0	0	0.092
Machine i=9	0	0.483	0	0	0	0	0	0
Machine i=10	0	0	0	0	0.53	0.356	0	0

Example 2	***Product 1***		***Product 2***		***Product 3***		***Product 4***	
	r=1	**r=2**	**r=1**	**r=2**	**r=1**	**r=2**	**r=1**	**r=2**
Machine i=1	0	0.579	0	0	0	0	0	0
Machine i=2	0	0.97	0	0.848	0	0	0	0.641
Machine i=3	0	0	0	0	0	0	0	0
Machine i=4	0.91	0.701	0.561	0	0	0	0	0
Machine i=5	0	0	0	0	0.208	0	0	0
Machine i=6	0.582	0.807	0	0.482	0	0.077	0	0
Machine i=7	0	0	0.272	0	0	0	0	0
Machine i=8	0.182	0	0	0	0	0	0.545	0.721
Machine i=9	0	0.568	0	0	0	0	0.506	0
Machine i=10	0	0	0.618	0	0	0	0.504	0

4.4. Performance evaluation

The 40 FCCD experiments illustrated in Table 4.10 were simulated and solved, using Lingo software. To ensure consistency in the results, only the four factors considered in the DOE varied; the rest of the parameters were kept constant.

The number of part types (P), number of operations for each part (R) and number of machine types varied as per DOE Table 4.10. The number of available locations in the facility was assumed to be the same as the number of machines. This means that all machines are used, and that each location will be occupied by a different one. No duplication of machines will take place in that scenario. Maximum number of machines in a cell was constrained between 1 and 6.

The distance matrix of locations λ_{kl} is calculated based on the derivations discussed in Section 3.2.4; it depends on which layout is being used: traditional rectangular (*R*) or circular layout (*C*). The inter-cell material handling cost was assumed to be \$100/m, and intracellular material handling cost was assumed to be \$1/*m*. A large difference in cost between the two was assumed to discourage intercellular material handling except when deemed necessary.

Machine parameters including purchasing, overhead, installation, uninstallation, variable costs and machine capacity are assumed to be identical for all machines and are given in Table 4.12. The routing sequence of each product and the processing time it takes to perform this operation on that machine are obtained using the random function generator, as explained in the previous section according to the FCCD. The demand for the product is assumed to be 5000 units /product type. Increasing the number of products results in increasing the total demand, thereby the quantity produced. If *P*=4, then total quantity produced by factory (*Q*) = 4 x 5000= 20,000 units, while if *P*=10 units then *Q*= 10 x 20,000=200,000 units. Increasing *P* increases the production quantity.

Table 4.12: Purchasing cost, Overhead Cost, Installation Cost, Uninstallation Cost, Unit variable Cost, Capacity of any machine

γ_i(\$)	β_i(\$)	δ_i(\$)	θ_i(\$)	μ_i(\$/h)	C_i(h)
15000	1400	400	400	7	5000

The above parameters were used to run the Lingo formulation and solve each of the scenarios for the optimum cost. Each of the cases were run twice with different values for the processing time, thus generating two random scenarios with the same process parameters. Results for the optimized total cost (avg. cost) for both duplicates in each of the runs are listed in Table 4.13. Minitab software was used to analyze response. The average cost varies between \$80,481 and \$212,917 with a mean of \$129,444.6 and a standard deviation of \$28,0003. The range is \$ 132,436, revealing that altering the layout, number of products, routing and machines can significantly influence the production cost.

Table 4.13: optimized total cost

Run Order	Avg. Cost	Run Order	Avg. Cost
1	90874	21	121913
2	118764	22	121913
3	129719	23	129719
4	159896	24	212917
5	117845	25	80481
6	121913	26	129719
7	172806	27	149582
8	129719	28	129719
9	148263	29	121913
10	121913	30	172602
11	142267	31	116134
12	212917	32	124014
13	104015	33	123815
14	136793	34	115122
15	148091	35	104015
16	116134	36	121913
17	81245	37	132045
18	121913	38	115867
19	129719	39	139796
20	118656	40	91122

Minitab software was used to perform response surface regression to model the effect of the process factors (# of products, # of machines, # of operations/routing and layout) on the total cost. The following model was obtained with *R2*= 71.83 % and *R2* adjusted=57.75 %. The model is fully quadratic with linear terms. The linear interaction terms and quadratic terms are illustrated in Equations 21 and 22.

Regression equation in encoded units

Layout= C

Total Cost (C) = 792494 - 38418 Product - 150213 Routing - 51295 Machines (21)

- 655 Product*Product + 2215 Routing*Routing

+ 996 Machines*Machines + 8828 Product*Routing + 1852 Product*Machines

+ 5061 Routing*Machines

Layout= R

Total Cost (R) = 560525 - 27019 Product - 123529 Routing - 45325 Machines (22)

- 655 Product*Product + 2215 Routing*Routing

+ 996 Machines*Machines + 8828 Product*Routing + 1852 Product*Machines

+ 5061 Routing*Machines

Equation 21 and 22 are rewritten in coded units as

Layout= C

Total Cost (C) = 2215 R^2 - 655 P^2 + 996 M^2 + 8828 PR + 1852 PM + 5061RM (23)

- 150213 R - 38418 P - 51295 M + 792494

Layout= R

Total Cost (R) = 2215 R^2 - 655 P^2 + 996 M^2 + 8828 PR + 1852 PM (24)

+ 5061 RM - 123529 R - 27019P - 45325M + 560525

Where,

P = Products

R = Routing

M = Machines

P^2 = Products*Products

R^2 = Routing*Routing

M^2 = Machines*Machines

PR = Products*Routing

PM = Products*Machines

RM = Routing*Machines

Figure 4.20 shows the main effect plot for the total cost. Increasing the quantity produced (as indicated by the product) or the variety (as indicted by routing) or complexity/hard product variety (as indicated by number of different machines) results in a significant increase in production cost. Increasing the number of products or demand adds to the cost, but also shifts towards hard product variety that requires different processes which cannot be performed using the same machine. This results in the highest additions to the cost. This relationship is non-linear and somewhat parabolic. An approximate linear rise in total cost occurs when the number of product types and routing is increased. The objective of the research was to examine the effect of the layout. Shifting from a rectangular layout to a circular layout reduces the total cost considerably. An average cost saving of 14 % ((140506-123104)/123104) was achieved in the case studied for a circular layout compared to the rectangular one. Routing had the least effect; this could be attributed to the fact that the numerical model already optimized the material handling cost.

The interaction between the different factors is shown in Figure 4.21. Almost all factors exhibit an interdependent behavior to various degrees. The main highlight of the interaction plots is the effect of the layout with other factors. It should be noticed that, for a small number of routing, machines and products, the proposed circular layout is more expensive than the traditional rectangular layout, but as the factory becomes larger with higher demand and more complex product/s, the cost of the circular layout becomes lower in comparison to the rectangular layout. This also indicates that break-even analysis can be conducted by factories to determine whether they are large enough to move to a circular layout or have to maintain the traditional rectangular alternative.

Figure 4.22 shows a surface plot at specific values of p, r, m and layout. The nonlinearity in the model due to quadratic terms and interaction terms is apparent. The proposed model can be used to determine the cost as a function of those four variables without the need to resort back to running simulations/ the lingo optimization model. One of the main drawbacks of running the optimization model is the high computational time, especially as the complexity of the problem increases. Utilizing equations 21-22 to predict the cost might help in providing a quick approximate solution to the problem.

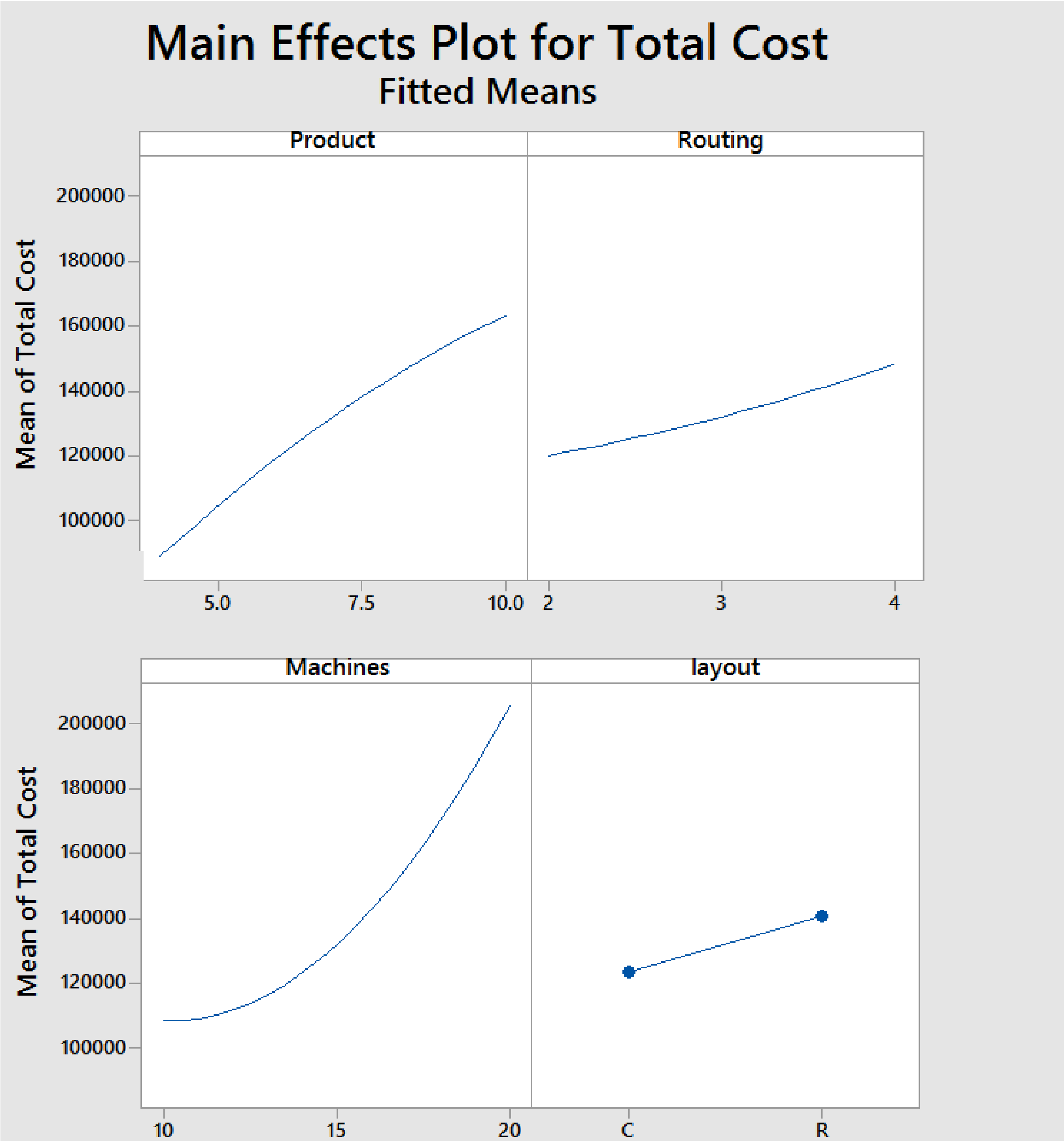

Figure 4.20: Main effect plot for total cost

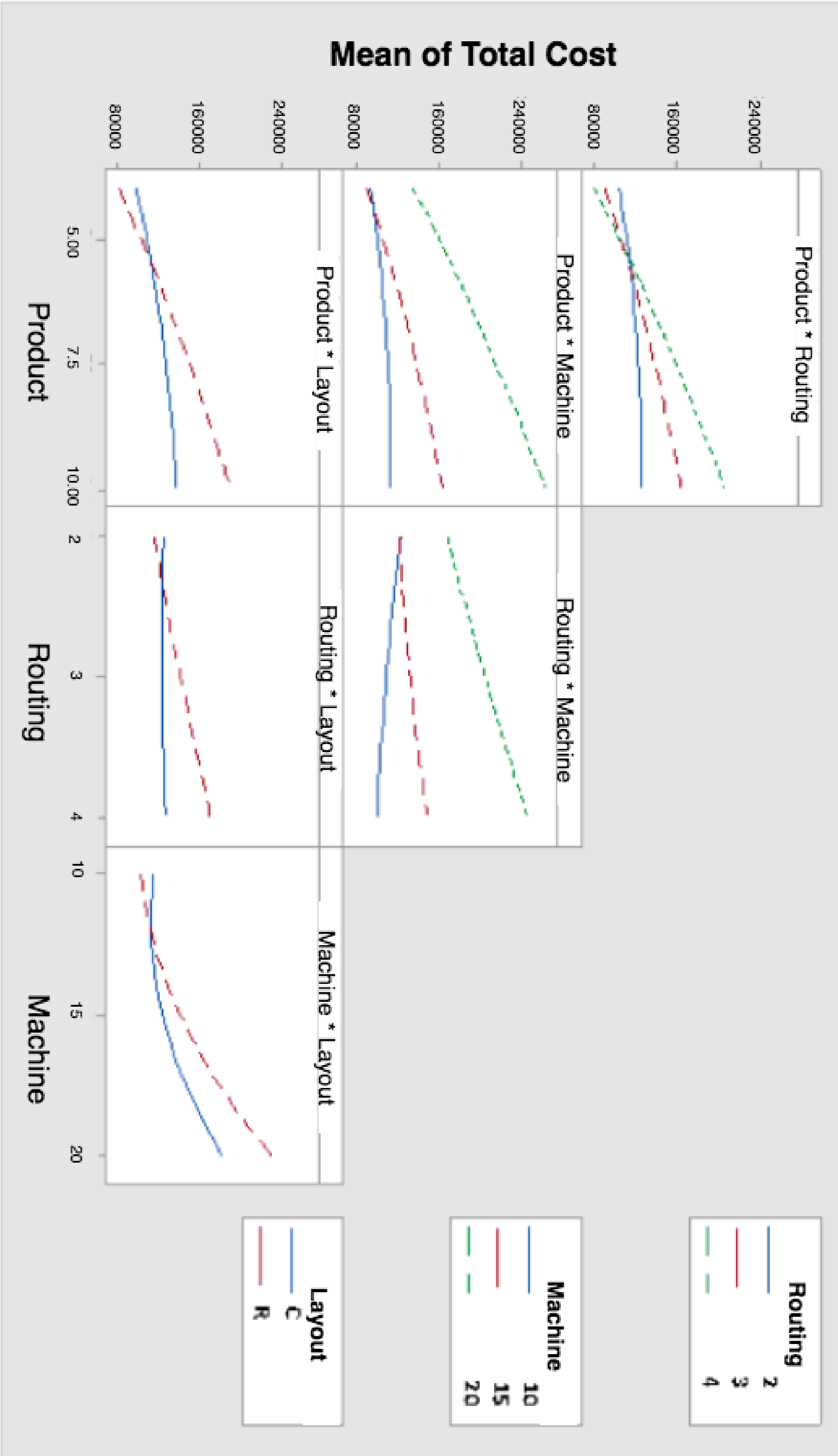

Figure 4.21: Interaction plot for total cost

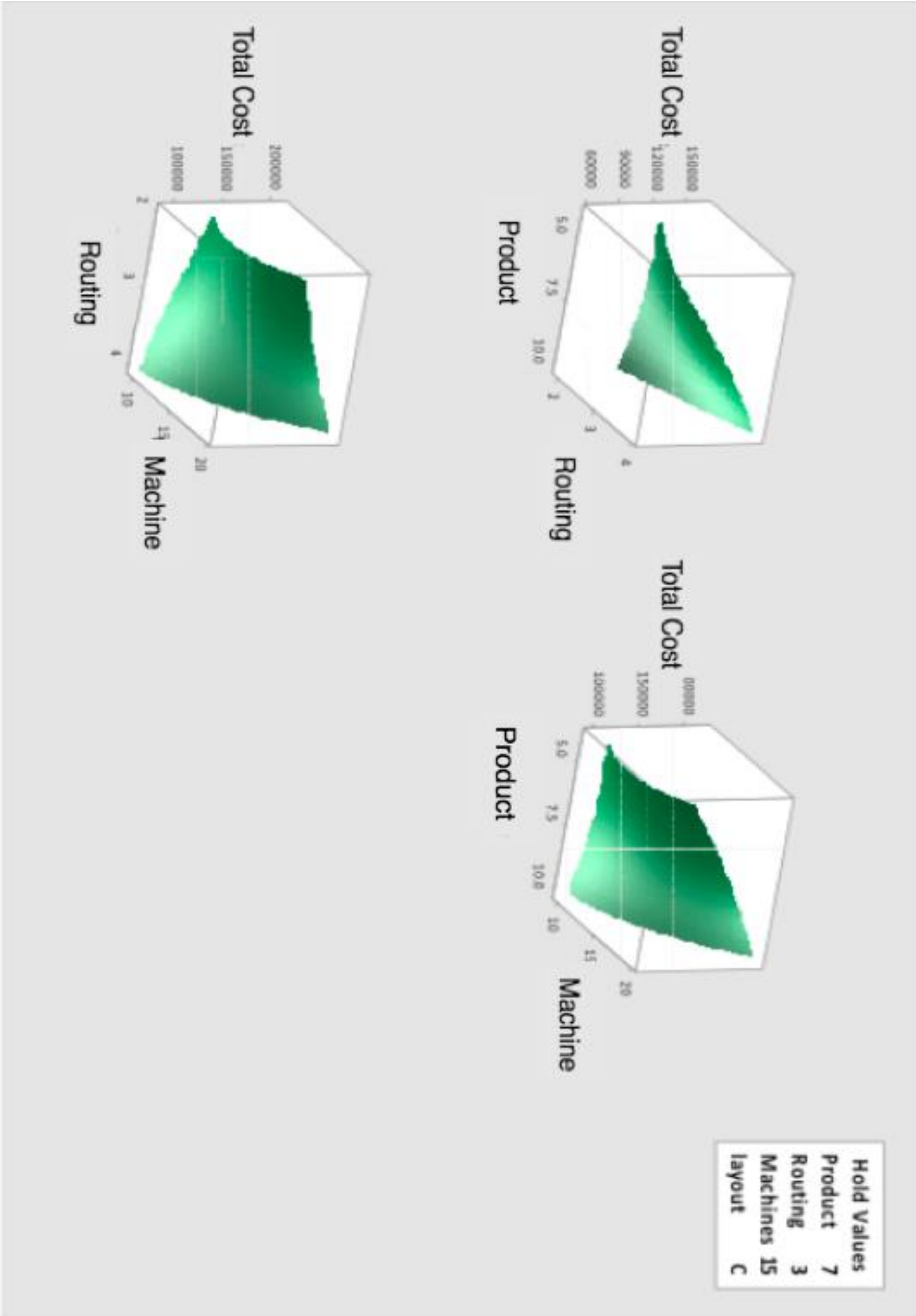

Figure 4.22: Surface plot of total cost with p=7, r=3, m=5 and a circular layout

Chapter 5. Conclusion

It is imperative to be able to meet the ever increasing demand for customized products with a shorter life cycle. Industries ought to be sufficiently flexible and able to respond to customer requirements. To achieve this, they may have to invest lots of money in building reconfigurable configurations. This study proposes a flexible manufacturing system layout based on the combination of an open field layout and a robot- centered cell layout. The synthesis, involving features from these two layouts, is used to create a circular layout which is considered to be more efficient and less expensive than the traditional rectangular open field layout.

Linear programming tools and logic algorithms were used to formulate the problem and optimize the layout in both scenarios: rectangular and circular layouts. Design of experiments was used to determine the right combination and order of variable values, and the necessary runs to compare between layouts. Results reveal that the proposed circular layout is a promising alternative that should be adopted by industries if they are in pursuit of flexible, cheaper and cost effective solutions. The layout is specifically more effective when the production process is more complex with higher demand and greater variety. Cost saving reaching 14% and machines. Such models could be used as alternative tools to provide a quick approximate estimate cost in case it is needed without resorting to solving complex optimization problem.

As any model, the circular layout certainly has some limitation such as it is not practical with small number of machines, small amount of products, and/ or very limited number of routings. While on the bright side, it is more efficient with complicated number of elements. Another disadvantage is that circular layout best applied in only facilities that have a square shape so that the entire layout can be utilized. Otherwise, the longest radius to be applied is the width, which indicates that the extra area of (length – width) will be idle.

For the Future, the model can be improved as a dynamic forecasting in terms of demand as well as adding uncertainty to the picture. Another approach is to unified the directions of material handling system as a single direction instead of multi and comparing the effect of this approach towards total cost.

Appendix A

Matlab code for the distance matrix in a circular layout (Horizontal)

```
By=   % length of the area;
L=    % Length of machine;
W=    % Width of machine;
A=    % aisle space;
ro=   % inner radius;
TM=0;
loop=ceil((0.5*By-ro)/(L+A));
Area = pi*((loop*(L+A)+ro))^2
By=(2*loop*(L+A)+ro);
for i=1:loop
    r(i)=ro+(i-1)*(L+A);
    m(i)=2*pi*r(i)/(W+A),1;
    m(i)=floor(m(i));
    Ith(i)=360/m(i);
    th(i,1)=0;
    for j=1:m(i)
        rm(i,j)=r(i);
        if j>1
            th(i,j)=th(i,j-1)+Ith(i);
        end
        TM=TM+1;

        Full(TM,1)=  TM;
        Full(TM,2)= i;
        Full(TM,3)=th(i,j);
        Full(TM,4)=rm(i,j);
        Full(TM,5)=Ith(i);
    end
end
x(TM,TM)=0;
for s=1:TM
```

```
    for m=1:TM

        if s==m
            x(s,m) =0;  % from - to the same machine distance is zero
        else
            sm=min(m,s);
            la=max(m,s);
            % loop on inside
            xinside= (Full(la,4)-Full(sm,4))+
(2*pi*Full(sm,4)*min(abs(Full(s,3)-Full(m,3)),360-abs(Full(s,3)-
Full(m,3)))/360);
           if Full(sm,4)==Full(la,4)
               xoutside=10000000;
           else
               % loop on outside
               xoutside= (Full(la,4)-Full(sm+(360/Full(sm,5)),4))+
(2*pi*Full(la,4)*min(abs(Full(s,3)-Full(m,3)),360-abs(Full(s,3)-
Full(m,3)))/360);
           end
            x(s,m)=min(xinside,xoutside);
        end
    end
end
```

Appendix B

MATLAB Code for rectangular layout

```
L=    % length of machine;
 W=   % width of machine;
 AL=  % aisle space;
n=    % number of machines in each column;
p=    % number of machines in each row;
Bx=n*(L+AL)+AL;
By=p*(W+AL)+AL
Area= (n*(L+AL)+AL)*(p*(W+AL)+AL)
machines=n*p
loc=0
x(n*p)=0;
y(n*p)=0;
incy=W+AL;
C=sqrt(Area/(pi))

for j=1:p
    incy=(AL+0.5*W)+(W+AL)*(j-1);

    for i=1:n
        incx=(AL+0.5*L)+(L+AL)*(i-1);
        loc=loc+1
        if loc==1
            x(loc)=AL+0.5*L;

            y(loc)=AL+0.5*W;
        end

        if loc>1
            x(loc)=incx;
            y(loc)=incy;
        end
```

```
    end
    incy=y(loc)+(W+AL)
end
for i=1:loc
    for j=1:loc
        lamda(i,j)=abs((x(j)-x(i))+(y(j)-y(i))); % distance between
each machine;
    end
end
```

Appendix C

Matlab random function generator

```
Pi= round(random('ev',0,1,[i,j])    ,r);

for i=1:18

for j=1:3

if (Pi(i,j)>1)
    Pi(i,j)=0;
else if ((Pi(i,j)<0))

    Pi(i,j)=0;
    end
end

end

end
```

Appendix D

Lingo Code for minimizing total cost

```
Model:

Sets:
Vp      :Rp, E, A;
Vr      ;
Vc      ;
Vd      ;
Vk      ;
Vl      ;
Vi      :La1,La2, La3, La4, La5, Ci;

Link_1 (vp) : Dp;
Link_2 (vk,vl) : Lamda;
Link_3 (vp,vr,vi) : pi, alpha;

Link_4 (vc,vk,vi) :x;
Link_5 (vk,vi) : y, yn;
Link_6 (vp,vr,vc,vk,vi) :Ws;
Link_7 (vp,vr,vc,vd,vk,vl,vi,vi) :Wl;
Link_8 (vi) :Q;

Endsets

Data:
Dp=;


pi=;

alpha=;

La1=;

La2=;


La3=;


La4=;


La5=;

lamda =;

ci=;
E=;
A=;
Value_U=;
Value_L=;

Enddata
```

```
R_size = @size(vr);



! [1] objective function;
Min= @sum(vp(p):
@sum(vr(r):
@sum(vc(c) :
@sum(vd(d)| d #NE# c:
@sum(vk(k):
@sum(vl(l):
@sum(vi(i):
@sum(vi(j):
wL(p,r,c,d,k,l,i,j)*lamda(k,l))*E(p)
)))))))
+ @sum(vp(p):
@sum(vr(r):
@sum(vc(c) :
@sum(vk(k):
@sum(vl(l):
@sum(vi(i):
@sum(vi(j):
wL(p,r,c,c,k,l,i,j)*lamda(k,l))*A(p)
))))))
+ @sum(vc(c) :
@sum(vk(k):
@sum(vi(i):
x(c,k,i) * la3(i)
)))
+
@sum(vp(p):
@sum(vr(r):
@sum(vc(c) :
@sum(vk(k):
@sum(vi(i):
ws (p,r,c,k,i) * pi(p,r,i)* la4 (i)
)))))
+ @sum(vi(i):
q(i) * La5(i)
)
+ @sum(vc(c) :
@sum(vk(k):
@sum(vi(i):
x(c,k,i) * la1(i)
)));

!@for (vp(p):
@for (vr(r):
@for (vi(i):
alpha (p,r,i) = @if( Pi (p,r,i)#gt# 0 ,1,0)
)));

! [2];
@FOR(vp(p):
@FOR(vr(r):
@FOR(vc(c):
@FOR(vk(k):
@FOR(vi(i):
Ws(p,r,c,k,i) <= x(c,k,i)* alpha(p,r,i) * Dp(p)
```

```
)))));
! [3];
@FOR(vp(p):
@FOR(vr(r):
@SUM(vc(c):
@SUM(vk(k):
@SUM(vi(i):
Ws(p,r,c,k,i)
)))
= Dp(p)
));
! [4];
@FOR(vk(k):
@SUM(vc(c):
@sum(vi(i):
X(c,k,i)
)) <= 1
);
! [5];
@FOR(vc(c):
@SUM(vk(k):
@sum(vi(i):
X(c,k,i)
)) <= Value_U
);
! [6];
@FOR(vc(c):
@SUM(vk(k):
@sum(vi(i):
X(c,k,i)
)) >= Value_L
);

! [7] ;
@FOR(vk(k):
@FOR(vi(i):
@SUM(vp(p):
@SUM(vr(r):
@SUM(vc(c):
Ws(p,r,c,k,i) * Pi(p,r,i)
)))<= Ci(i)
));
! [8];

@FOR(vr(r)| r #LT# r_Size:
@FOR(vp(p):
@FOR(vd(d):
@FOR(vl(l):
@FOR(vi(j):
@SUM(vc(c):
@SUM(vk(k):
@SUM(vi(i):
wL(p,r,c,d,k,l,i,j)
))) = Ws(p,r+1,d,l,j)
)))));
! [9];
@FOR(vr(r)| r #LT# r_Size:
@FOR(vp(p):
@FOR(vc(c):
```

```
@FOR(vk(k):
@FOR(vi(i):
@SUM(vd(d):
@SUM(vl(l):
@SUM(vi(j):
wL(p,r,c,d,k,l,i,j)
))) = Ws(p,r,c,k,i)
)))));

! [11];

@FOR(vi(i):
@sum(vc(c):
@SUM(vk(k):
x(c,k,i)
)) =
Q(i)
);
! [14];
@FOR(vi(i):
@FOR(vk(k):
@FOR(vc(c):
@bin(x(c,k,i))
)));
@FOR(vi(i):
@FOR(vk(k):
@bin(y(k,i));
@bin(yn(k,i));
));

@FOR(vr(r):
@FOR(vp(p):
@FOR(vc(c):
@FOR(vk(k):
@FOR(vi(i):
@FOR(vd(d):
@FOR(vl(l):
@FOR(vi(j):
@gin(wL(p,r,c,d,k,l,i,j));
))))))));

@FOR(vr(r):
@FOR(vp(p):
@FOR(vc(c):
@FOR(vk(k):
@FOR(vi(i):
@gin(Ws(p,r,c,k,i)); )))));
```

Appendix E

MATLAB Code for circular layout

```
By=;
for j=1:
   ro=0;
for i=1:
    Machinesw=myfunw(ro,By);
    Mw(i)=Machinesw;
    Machines=myfun(ro,By);
    M(i)=Machines;
    r(i)=ro;
    ro=ro+0.25;
end
figure
plot(r,Mw,'x-')
hold on
plot(r,M,'d--')
xlabel('ro')
ylabel('Max number of machines')
legend ('horizontal','vertical')
title(By)
By=By+1;
end

function TM = myfunw( ro, By )
L=;
W=;
A=;
TM=0;
loop=round((0.5*By-ro)/(L+A));
By=(2*loop*(L+A)+ro);
for i=1:loop
    r(i)=ro+(i-1)*(L+A);
    m(i)=2*pi*r(i)/(W+A),1;
    m(i)=floor(m(i));
    Ith(i)=360/m(i);
    th(i,1)=0;
    for j=1:m(i)
        rm(i,j)=r(i);
        if j>1
            th(i,j)=th(i,j-1)+Ith(i);
        end
        TM=TM+1;
        Full(TM,1)=  TM;
        Full(TM,2)= i;
        Full(TM,3)=th(i,j);
        Full(TM,4)=rm(i,j);
        Full(TM,5)=Ith(i);
    end
end

end
```

```
function TM = myfun( ro, By )
L=1.5;
W=0.75;
A=0.5;
TM=0;
loop=round((0.5*By-ro)/(L+A));
Area = pi*((loop*(L+A)+ro))^2;
By=(2*loop*(L+A)+ro);
for i=1:loop
    r(i)=ro+(i-1)*(L+A);
    m(i)=2*pi*r(i)/(W+A),1;
    m(i)=floor(m(i));
    Ith(i)=360/m(i);
    th(i,1)=0;
    for j=1:m(i)
        rm(i,j)=r(i);
        if j>1
            th(i,j)=th(i,j-1)+Ith(i);
        end
        TM=TM+1;

        Full(TM,1)=  TM;
        Full(TM,2)= i;
        Full(TM,3)=th(i,j);
        Full(TM,4)=rm(i,j);
        Full(TM,5)=Ith(i);
    end
end

end
```

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